Design and Performance Analysis of MAC Protocol for Wireless LAN

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ABSTRACT

In recent years, much interest has been involved in the design of wireless LAN (WLAN). In the medium access control (MAC) layer of WLAN, there is only one logical channel designed, so different mobile stations will contend for the control of the transmission media. Then MAC layer protocol should provide efficient contending mechanism for the users to share the limited spectrum resources. Nowadays, the DCF and EDCF, which supports different kinds of service, become the basis of the IEEE802.11 standard on the MAC layer.

However, it is observed that the primary deficiency of the current MAC protocol is to use the binary increasing-only mechanism. DCF absorbs the number of collisions as the condition to derive the contention window (CW). Whereas the transmission history is not the direct factor influencing the future collision probability. It is actually used to estimate the number of active nodes in the Wireless LAN, which dominates the frame delay and system performance. The major advantage of DCF is simplicity and distributed algorithm, which are important in the Wireless LAN.

Fortunately, in the infrastructure wireless LAN, it is not too difficult to get partial global information. Then we can combine the distributed and central control algorithms to get more credits. In the infrastructure Wireless LAN, the network core is Access Point (AP), and all the mobile stations cooperate under the control of the AP. In this case AP can collect the distributed contention information and derive the

optimized CW based on the number of the active mobile stations in the next contention cycle. It will broadcast the control information if necessary and all the nodes will adjust their behaviours accordingly. Consequently, the system performance can be improved significantly by reducing the overheads, idle time slots and collisions.

Nowadays high transmission rate and the service differentiation are putted forward for the future Wireless LAN. The frames from the upper layers will be sorted to distinct queues according to their QoS requirements. Then there are multiple service queues instead of one in DCF. Therefore we extend our proposed protocol mentioned above and introduce the recursive balance method to derive different proper queues for all queues. The method can remarkably decrease the delay of time sensitive frames without influencing others' performance significantly.

Both protocols can be implemented in the actual Wireless LAN easily just by updating the software.

摘要

近年來，無線局域網設計受到了越來越多的關注。在無線局域網的媒介介入控制子層，由於只存在一個邏輯通道，所以許多移動終端將不得不競爭使用該傳輸資源。於是媒介介入控制子層協議就必須能夠提供高效的演算法機制來控制這些移動終端對於邏輯通道的共用。如今，分佈式協作算法和改進的分佈式協作算法成爲了國際電子電氣工程師協會所制定的 802.11 標準之基礎。

然而，現行的媒介介入控制子層協議的缺點也是很明顯的，就是使用指數單方向增加的機制。分佈式協作算法使用某個幀遇到的衝突次數來決定下一次競爭窗的大小。可是，以前的衝突次數與未來衝突概率並沒有直接的關係。衝突次數只是用來預測局域網內活躍移動終端的個數。後者才是真正直接影響傳輸延遲和系統性能的參數。802.11 標準使用分佈式協作演算法主要爲了簡單。

但是，在我們最常使用的基礎節點型的無線局域網中，得到部分全局資訊並不是非常困難。這樣，我們可以綜合分佈式算法和中央控制式算法的優點。在基礎節點型的無線局域網中，總存在一個作爲核心的接入點。所有該局域網的移動終端必須受該接入點的控制。所以接入點就能夠很容易的收集各個節點的競爭資訊，從而得到最好的競爭窗大小。然後，在需要的時候，接入點就可以告知所有的移動終端最近的競爭視窗大小，同時移動終端也就可以以此調整自己的參數。整個系統的性能從而得到大大的提高。

另外，現在人們對於未來的無線局域網提出了高的傳輸速率和服務劃分的要求。從上層到達媒介介入控制子層的幀將按照他們各自不同的服務要求被分類到

不同的隊列中。這樣在改進的分佈式協作算法，一個移動終端中就同時存在多個隊列。於是我們也改進了我們本來提出的協議，使用遞迴平衡算法來得到適合不同隊列的競爭窗的大小。這個算法可以大大減少時間敏感服務的傳輸遲延，同時對於別的服務也不額外造成很大影響

我們提出的協議，無論是基本類型還是改進類型，都可以直接通過升級軟體在實際的無線局域網中得到應用。

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CHAPTER I

Introduction to Wireless LAN

Nowadays, broadband access and wireless are two of the most developing directions in communication system. As in the wireless communication, Wireless LAN (WLAN) seems to overcome many technologies, such as Bluetooth and HomeRF, and become the most hopeful solution for local area network (LAN). In this thesis, we concerns on the performance of Wireless LAN and propose a new protocol to improve the system efficiency.

Abstract

In this chapter, we will introduce some background knowledge about the Wireless LAN, based on which we can improve our research.

- Wireless LAN Network Architecture

  In this part, firstly we will give the normal definition of Wireless LAN. Secondly, we introduce the structure of the most deployed Wireless LAN, after which we explain the communication manner.
- IEEE 802.11 protocol family

  The protocol family made by IEEE 802.11 working group has become the standards for the Wireless LAN. In this part we will introduce the history of IEEE 802.11 protocol family and major protocol layers compared with the OSI model. Last the separate characterises of different protocols will be specified.
- The Major factors influencing the System Performance

  There are three kinds of factors influencing the system performance most, which are transmission media, topology and media access control (MAC). In this part,

we will briefly explain influence caused by the former two factors and then concentrate on the MAC technology.

- Research Object

  In the most popular MAC protocol, there are two kinds of overheads, idle time slots and penalty of collisions. In this part, we briefly introduce the cause of the overheads and propose the main idea of our solution.

- Overview

  We explain the structure of the whole thesis.

1.1 **Wireless LAN Network Architecture**

Currently there are many circumscriptions for the Wireless LAN. Normally we accept two definitions. Generally any network connecting different stations via wireless media in certain area can be called Wireless LAN. Its counterpart is Wireless Wide Area Network (WWAN), such as GSM/GPRS and CDMA networks. This kind of definition refers to many kinds of Wireless LANs and many standards. However, there are two major directions, one designed for the high transmission rate (IEEE 802.11), the other designed for the low rate and short transmission distance (Bluetooth, HomeRF and HiperLAN). In the view of future network, the IEEE 802.11 protocol family will be broadly adopted and become the actual standards for the Wireless LAN.

In narrow sense, Wireless LAN is normally referred as the network conforming to the IEEE 802.11 protocol family, which is also the definition in many papers and journals. So we employ this definition without any special notice in this thesis. IEEE 802.11 protocol family contains IEEE802.11, IEEE802.11a, IEEE802.11b, IEEE802.11g and so on. The protocols made by Institute of Electrical and Electronic Engineers (IEEE) have become the practical standards in these years. The details of these protocols will be introduced in the next part.

Before discussing different structures of the Wireless LAN, we give the definitions of devices used in the Wireless LAN. There are only four device names used in the IEEE 802.11 standards ([1], [2]):

- ✧ Station (STA): The device containing the wireless media interfaces for MAC and PHY layers
- ✧ Mobile Station: One kind of station that can communicate in motion.
- ✧ Portable Station: One kind of station that can move from one place to another, but perform communication only in a fixed position
- ✧ Access Point (AP): An entity that has the station function and provides distributed access service for the nodes connected to it

(Notice: [3] is European standards and has the similar definitions and mechanism counterpoint as [1], [2])

The most deployed Wireless LAN can be shown in Fig. 1.1. It is commonly called "Infrastructure Wireless LAN", which is compared with ad-hoc network. The differences between them will be explained in the Chapter 1.3. Up to day the infrastructure network has been deployed in most of places and become the actual standard mode for the Wireless LAN.

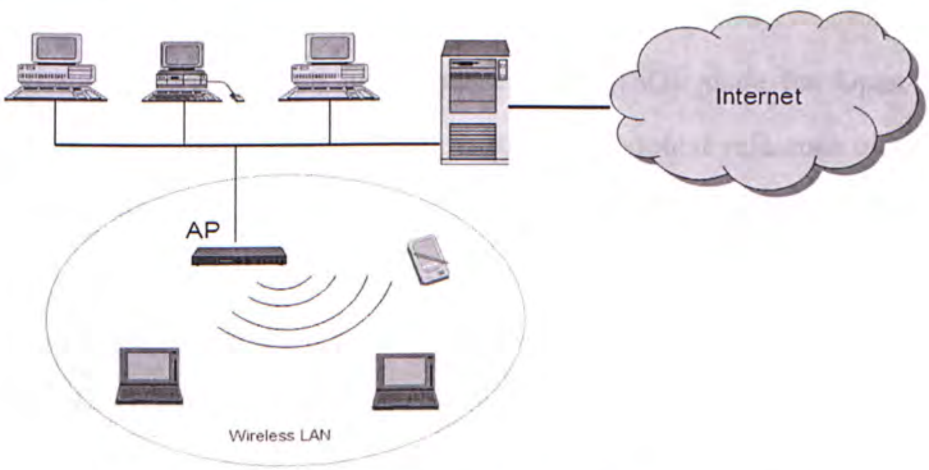

Fig 1.1 The Structure of Most Deployed Wireless LAN

As shown in the Fig.1.1, in order to access to the Internet or external network, there always exists an Access Point (AP), which is the core of the Wireless LAN. All other stations should be in the transmission area of AP to guarantee that they can connect to AP at any time. If we consider the Wireless LAN as a close entity, AP is the only channel to the external network. There are usually wired media connecting the external network and AP. But sometimes we still use the wireless media to link the two parts.

In the Wireless LAN as in Fig. 1.1, AP is the interface for the authentication and all stations must get the permission before entering some Wireless LAN. AP is also responsible for the network corporation. The stations must transmit their packets to the AP first no matter the destinations are in the same cell or not. For example, when a station needs the service in a remote server in the Internet, it sends its packet to the AP and AP then forward packets to the wanted server. The same thing happens that when station A and station B, which are in the same wireless LAN, want to communicate with each other, A must send its packets to AP, and former can forward the packets to B.

1.2 IEEE 802.11 Protocol family

The International Organization for Standardization (ISO) made the Open System Intercommunication (OSI) model, which is the most popular reference model when we design or analyze the network protocol. There are 7 layers in the OSI, which are Physical layer, Data link layer, Network layer, Transport layer, Session layer, Presentation layer, Application layer. The LAN protocol structure always includes the physical layer, data link layer and network layer. What is more, because there are no routing problems in LAN, there is no specified network layer protocol; because Media Access Control (MAC) in the LAN is complicated, the data link layer is divided into two sub layers, which are Logical Link Control (LLC) layer and MAC layer. The wireless LAN protocol deals with the physical layer and MAC layer, which are shown in the Fig. 1.2.

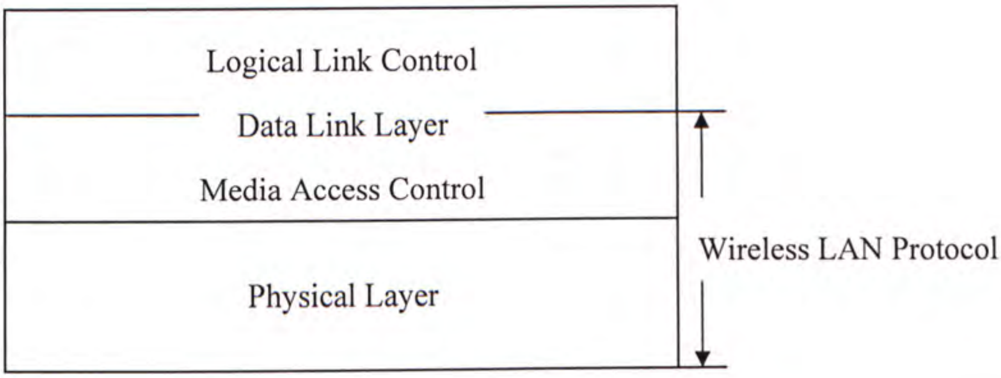

Fig. 1.2 The Protocol layers for the Wireless LAN

As the explanation above, the Wireless LAN can harmonize easily in the LAN. What we need is just to produce the devices which follows to the Wireless LAN protocol in the lower two layers. However, it is not meaning that the Wireless LAN Protocol does not involve anything in the upper layer. There are still some complicated cases that will influence the procedures in the upper layers. For example, in Wireless LAN, all the stations are mobile. They can leave from one position and appear somewhere else, which transitorily blocks the transmission. This property will cause some advanced function confusions in network operation system because the nodes are proposed to stay still. Another example is that the delay in the Wireless LAN is relatively bigger for the low transmission rate. In this case, some network programs needing response in certain time period have to adjust accordingly.

IEEE 802.11 protocol family is made by Institute of Electrical and Electronic Engineer (IEEE). All the protocols, including many released standards and proposed standards, are based on the IEEE 802.11. Fig. 1.3 shows the status of IEEE 802.11 in the IEEE network protocol system. And Table 1-1 shows the protocol names, released time and brief explanation.

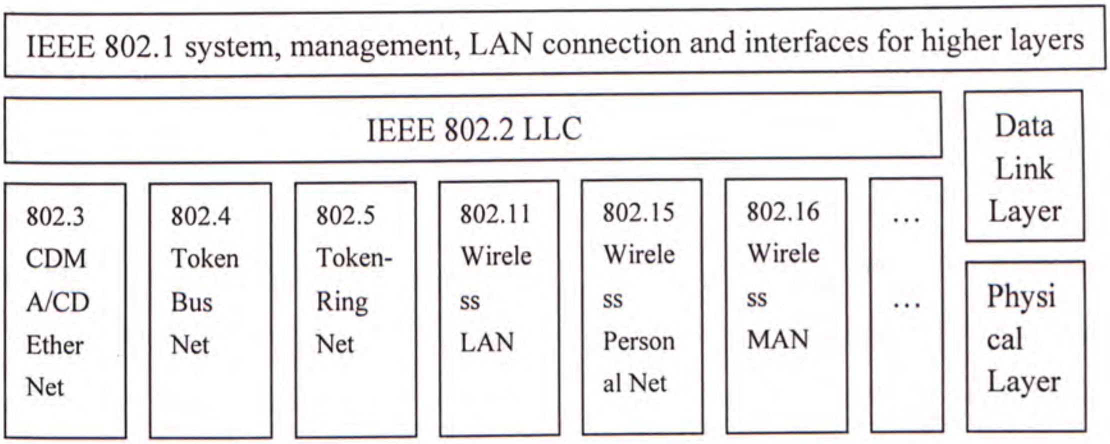

Fig. 1.3 The status of 802.11 in the IEEE network protocol system

Table 1-1 IEEE 802.11 protocol family

Protocol Name	(Proposed) Released Time	Explanation
IEEE 802.11	1997	The standard of MAC, and PHY for 2.4G Hz RF and IR
IEEE 802.11a	1999	The standard of MAC, and PHY for 5G Hz
IEEE 802.11b	1997	The standard of MAC, and extended PHY for 2.4G Hz (DSSS)
IEEE 802.11b+	2002	The standard of MAC, and extended PHY for 2.4G Hz (PBCC)
IEEE 802.11c	2000	Connection Protocol between 802.11 and Ether Network
IEEE 802.11d	2000	The standard for the International Roaming
IEEE 802.11e	2004	The standard for QoS issues in Wireless LAN
IEEE 802.11F	2003	The protocol for the transmission between APs when roaming
IEEE 802.11g	2003	The standard of MAC, and extended PHY for 2.4G Hz (OFDM)
IEEE 802.11h	2003	The standard of MAC, and extended PHY for 5G Hz (Europe)
IEEE 802.11i	2004	Enhanced security mechanism for Wireless LAN
IEEE 802.11j	2004	The standard of MAC, and extended PHY for 5G Hz (Japan)
IEEE 802.11k	2005	The normalization of RF measurement in Wireless LAN
IEEE 802.11l	None	None
IEEE 802.11m	2006	The normalization of device maintenance in Wireless LAN
IEEE 802.11n	2007	The protocol for high throughput (100M bps)

Notice: In the Table 1.1, all protocol names use the small letters, except IEEE 802.11F. What is more, the released time of many protocols in this table are not determined.

In the Fig.1.4, we show the distribution of the IEEE 802.11 protocols in different layers. However, IEEE 802.11 is not included because it is the fundamental protocol giving the standards of MAC, and PHY. All the offspring (IEEE 802.11a, IEEE 802.11b, IEEE 802.11g and future IEEE 802.11n) increasing the transmission rate inherit the MAC protocol in IEEE 802.11.

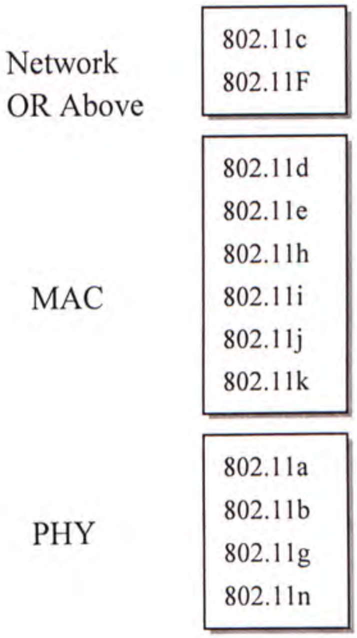

Fig. 1.4 The distribution of IEEE 802.11 protocol family

1.3 The Major factors influencing the System Performance

In the LAN, there are three major factors influencing the system performance mostly: transmission media, network topology and MAC. These three parameters largely deicide the kinds of service, network delay, throughput, efficiency and so on. Between former three ones, MAC, which is used to share the transmission resource, is even more important. It directly and significantly determines the system performance and efficiency.

Transmission Media

A kind of transmission media is needed to connect different PCs. In the wired LAN, we always use the coaxial cable, twisted pair line or optical fibre, which are usually called "bounded media". In the wireless LAN, infrared ray (IR) and microwave are our options. They are called "boundless media" because the signal energy does not stay in bounded area compared with the media used in wired LAN.

The bandwidth of IR locates between visible light and microwave. The primary advantage of IR is that transmission will not be interfered by microwave that is most popular media so far. However, any opaque objects will block IR transmission, so it is not very proper for the mobile communication.

In the microwave transmission, the baseband signal is removed to micro bandwidth to send. The whole procedure is similar to radio or TV. Microwave can traverse roadblock at some frequency points. This property enable microwave to be the favourite transmission media in the Wireless LAN, where the transmission must go through or bypass some walls, ceils, doors and such obstacles like that. On the other hand, microwave is easily intercepted.

Network topology

The architecture and connection between different devices are called network topology. Sometimes topology is referred as the physical distribution; however sometimes it is referred as the logical distribution. The physical topology is not always equal to the logical topology. For example, the Ethernet with a hub has a star topological structure physically and has a bus topological structure logically. Not to make some unnecessary confusion, we refer to the logical structure when we call topology in this thesis.

The Wireless LAN topology can be sorted into two parts: Ad-Hoc Network and Infrastructure Network.

Ad-Hoc network is composed by client stations as shown in the Fig. 1.5. All the stations will communication with each other directly. Normally this network can be accessed into wired network (However, sometimes one of stations will be the interface to the wired network. Then the whole network can connect to external network). In the ad-hoc network, one station must be in the transmission areas of some other stations; otherwise it is considered disconnected to this ad-hoc network. When the number of active station is too large, the channel contention will be drastic and the system performance will decrease quickly. So the ad-hoc is proper for the group with not many customers.

Fig. 1.5 The structure of Ad-Hoc network

The structure of Infrastructure Network is shown in Fig. 1.1. It is composed with base stations and client stations. The access and communication of all stations should be controlled by base station. Because of the central control and shorter covering area, the transmission rate in the infrastructure network is higher than that of ad-hoc network.

MAC

There are many communication manners in the computer network. Taking one with another, they can be classified into two parts: Point-to-point and Broadcast. Point-to-point communication means that there exits a physical channel uniquely occupied by the sender and receiver. There are no channel contention and no MAC problems either. Broadcast communication means that all stations in the network share only one channel. The packets sent by one station will be received by all the other ones. In the broadcast communication network, we must solve the media access problems because of the access collision. The method to assign transmission media to different users is Media Access Control (MAC). The corresponding protocol is MAC protocol. A good MAC protocol should be simple to implement, efficient in the resource utilization and fair to all users. All Wide Area Networks (WAN) use the Point-to-point manner except the satellite network. Inversely all LANs adopt the broadcast as the fundamental. So the MAC protocol is especially important in the LAN because we must assign the unique channel to different users.

There are two ways to assign one channel to different contenders: static assigning and dynamic assigning. In the static assignment, the channel is divided to different users and they share the media following to schedule made before hand. However when the number of customers varies, or the service burst happens, the performance of static assignment becomes poor. It is not suitable in the computer network. The dynamic assignment dynamically gives the channel access opportunities to users. It includes Contention Solutions and Reserve Solution. Contention Solution belongs to the Random Access technology. All the customers follow one protocol to contend the media. This solution is easy to implement and suitable for the low or medium system loading. However it also imports the collisions, which will decrease the whole performance badly when the loading is high. Reserve Solution divides the transmission time into little time slots. Any customer that wants to send its packets must apply to reserve some time slots before hand. This solution is commonly suitable for the high system loading.

There are two ways of Contention Solution for MAC in LAN, CSMA/CD and CSMA/CA. Both of these two ways belong to the dynamic assignment for the future network. In order to check whether others want to occupy the media at the same time, the customers will detect the signal energy in the channel. This technology is Carrier Sense Multiple Access (CSMA).

"Carrier Sense" means that the customers are detecting the network and send the packets until the transmission media is idle. This will avoid some collisions. "Multiple Access" means that many customers share the unique channel. All of them will detect the channel at the same time and use the Broadcast manner.

However in the high loading network, the collisions are still very common even with CSMA. Because two customers may find no signals in the bus line and try to send their packets meanwhile. These two signals will mix and no useful information can be received. The collisions need the customers to resend their frame and reduce the total performance. The more customers there are in the network, the higher the probability of collisions is. Therefore, it is very important to detect the collisions or avoid the collisions. So CSMA/CD (CD, Collision Detect) and CSMA/CA ([4], [5]) (CA, Collision Avoidance) are introduced.

CSMA/CD

In the CSMA/CD, every station decides to send the packets independently. When it is transmitting its packets, it is still "listening" to the channel to check whether others are using the media at the same time. If it "hears" others through signal detecting (such as unpredicted signal voltage change), it assumes that its packets have been lost for the collision in the channel. It will try to resend after a random backoff time, which is produced by MAC mechanism, to avoid the future collisions. This is technology is broadly used in the wired LAN.

CSMA/CA

CAMA/CA is another MAC method, which is the substitute of CSMA/CD when Wireless LAN is developing. In the wireless channel, the signal is fading quickly, distorted by the channel response and always interfered by the noises severely. So in the wireless LAN, it is impossible to detect the signal energy when sending as it does in the wired network. Then CSMA/CD is not suitable any more. In the CSMA/CA, our basic idea is to avoid collisions as much as possible instead of detecting collisions. We introduce a Network Allocation Vector (NAV), which shows residual media busy time. Each customer's NAV is updated from the MAC control frame and every customer will use the latest NAC and physical detecting to decide whether to send. Sometimes maybe the physical detecting shows that the transmission media is idle, however NAV notifies that the channel is busy. In this case, the customer cannot send its packet. It must wait to send until both of the NAV and physical detecting show the channel is not occupied by others. The NAV actually becomes virtual carrier sensing. The combination of NAV and physical carrier sensing constructs the collision avoidance mechanism in the CSMA/CA. The whole procedure of CSMA/CA is shown in the Fig. 1.6.

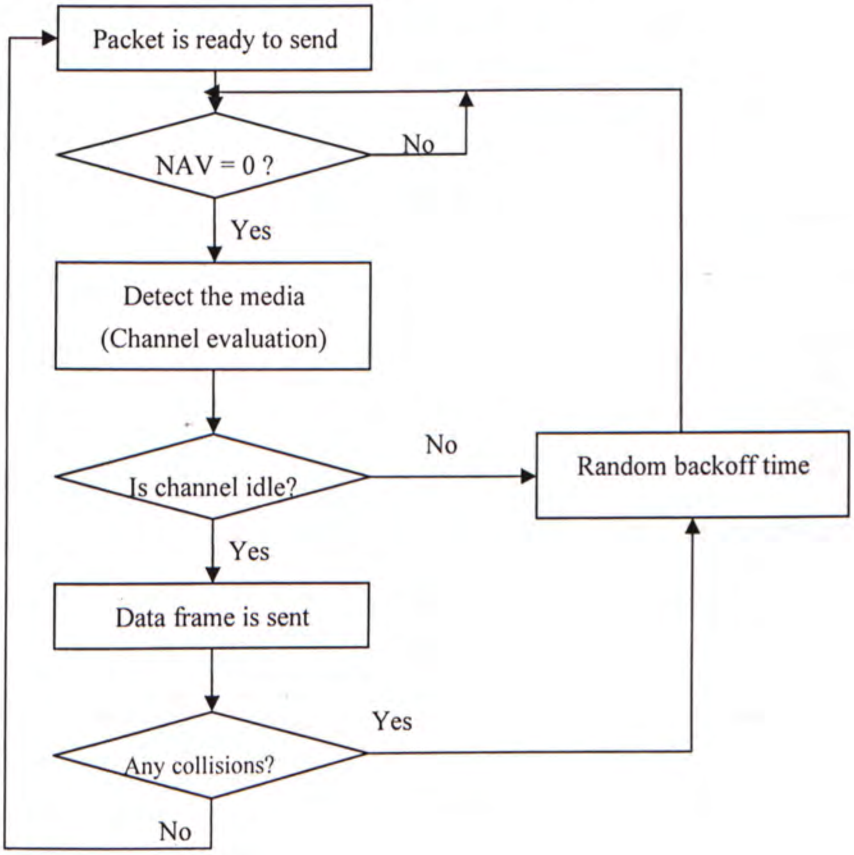

Fig. 1.6 CSMA/CA Procedure

Based on the CSMA/CA, IEEE 802.11 protocol family has found an algorithm to produce the random backoff time to share the transmission media more efficiently, which is DCF (Distributed Coordination Function) and its extended version EDCF (Enhanced Distributed Coordination Function). DCF or EDCF based on CSMA/CA becomes the basic structure of MAC protocol, which is our research beginning. (The details of DCF and EDCF will be introduced in the next chapter.)

1.4 Research Objectives

In this thesis, we investigate the efficiency of DCF and analyze its major disadvantages. We get its design ideas from formulas to produce the random backoff time. We point out its assumption and the corresponding deficiency.

We proposed a novel protocol suitable in infrastructure Wireless LAN on the foundation of DCF. In current DCF/EDCF algorithm, the nodes adjust their behaviours only based on the local information. However, it is not difficult to get the global information in the infrastructure wireless LAN. All the stations should send their packets to the AP no matter the destinations are in the same cell or not. So they can notify the AP whether it still has data to send after this transmission. With this contention information, AP estimates the number of the active mobile stations in the next contention cycle and then choose the optimized values for some system parameters. It will broadcast the control information when necessary. Then all the nodes could rectify the local values and modify their measures to share the transmission media more efficiently.

1.5 Overview

The report consists of six parts. In this part, we have outlined the brief introduction on the Wireless LAN as well as our research objectives. In Chapter 2, we will analyze the major deficiency of DCF, which is our motivation to improve the algorithm. Chapter 3 covers our proposed MAC protocol. This part just solves the problems with QoS in the current Wireless LAN. In Chapter 4, we first briefly explain how to realize the different priorities in the distributed algorithm in Wireless LAN. Then we introduce the advanced algorithm to consummate our proposed MAC protocol to fit the future network requirements. Chapter 5 includes some further research issues on our area. We get our conclusions and discuss the probable future directions in Chapter 6.

CHAPTER II

The Major Deficiency of DCF and Motivation

Abstract

In this chapter, we will clearly explain the procedure of DCF and its major deficiency. This is our research motivation. Then we will give our improvement direction, which is the path for the Chapter 3.

- DCF

  In this part, we will give some important definitions in the MAC layer, especially different kinds of IFS (Inter-Frame Space). Then we clearly describe the procedure of DCF, which produces the random back off time. This is the foundation of our further discussion.

- The Major deficiencies in the DCF

  In this part, first we analyze the formula that produces the counter value and point out the original design idea of DCF. However the algorithm in DCF is not suitable for all the conditions and not accurate. And we show the major two deficiencies of DCF, which are our research motivation.

- Improvement directions

  In this part, we give the basic design principles for MAC protocol in Wireless LAN. Then according to the principles, we introduce our solutions to these major deficiencies of DCF.

2.1 DCF

All stations in the Wireless LAN should send and receive the frames according to the standards. First we will give the definitions of frames in the MAC protocol. We introduce them in three ways, the structures, frame categories and IFS (Inter-Frame Space).

Frame Structure

In the Wireless LAN, the basic structure of a frame consists of three parts:

1. MAC Header: It contains the Frame Control (FC), Duration, Addresses, Sequence Control (SC) information and so on.
2. Variable Frame Body: It contains the Data according to different frame categories.
3. Frame Check Sequence (FCS): It contains IEEE 32 bits CRC.

The integrated frame structure in the IEEE 802.11 is shown in the Fig. 2.1. In this structure, Address 2, Address 3, Sequence Control, Address 4 and Frame body only appear in some frames.

	FC	Duration	Addr 1	Addr 2	Addr 3	SC	Addr 4	Data	FCS
No. of Bytes	2	2	6	6	6	2	6	0~2312	4

Fig. 2.1 The Frame Structure in the Wireless LAN

We do not introduce the details of the function of every part above. They are specified in the standards ([1], [2]). The IEEE 802.11 Frame structure is different from that of IEEE 802.3. In the practical network, AP is responsible to transfer one kind of frame to another.

Frame Category

There are three kinds of frames in the Wireless LAN, which are Control Frame, Management Frame and Data Frame as shown in the Table 2-1

Table 2-1 The Frame Categories in the Wireless LAN

Frame Category Name	Sub-category
Control Frame	Request to send/Clear to send (RTS/CTS) ACK Power Saving Poll (PS-Poll) Contention Free End (CF-End) Contention Free End and corresponding ACK (CF-End + CF-ACK)
Management Frame	Beacon ATIM Frame Deassociation Frame Association request/ Association ACK Reassociation request/ Reassociation ACK Inquiry request/Inquiry ACK Authentication Frame Deauthentication Frame
Data Frame	

Of all the frames above, the most import important ones in DCF are RTS/CTS, ACK and Data frame. They are necessary in any kinds of Wireless LAN. The details will be introduced in the later part.

IFS

It is difficult to understand the whole procedure of DCF without IFS knowledge. Different kinds of IFSs are indispensable parts in the whole mechanism. Here we first give the definition of every kind of IFS and then explain how they incorporate with each other. In the Wireless LAN, all the stations behave synchronously. IFS is derived from the standard timer in any IEEE 802.11 cell.

IFS is the space time between different frames, in which the stations detect the channel state through carrier sensing. In the standards, there are four kinds of IFSs totally.

- SIFS: Short Inter Frame Space
- PIFS: PCF (Point Coordination Function) Inter Frame Space
- DIFS: DCF Inter Frame Space
- EIFS: Extended Inter Frame Space

All of IFSs have none business of transmission rates. Every kind of PHY standard has its corresponding IFSs, whose values are determined by the PHY parameters. These four IFSs above are used to send some kind of information in the network, or used to control the time period when there happens a collision.

IFSs are usually united by μs. They can show the station access to the media or provide kinds of priorities. In one Wireless LAN, all procedures are synchronous. All stations or AP implement jobs in normal time periods. Every station is very aware of these IFSs and can employ them properly. All stations know how and when to implement a certain measure in the network.

Before discussing all the details of IFS, we should first introduce a normal time period, Time Slot. Time Slot is the foreword of all IFSs. The relationship between Time Slot and other IFSs can be derived from the formulas below.

$$\text{PIFS} = \text{SIFS} + 1\ \text{TimeSlot}$$

$$\text{DIFS} = \text{SIFS} + 2\ \text{TimeSlot}$$

PIFS and DIFS are the basic and most important IFS in the PCF and DCF. Because we concerns on the DCF, we will explain the DIFS and SIFS more clearly.

SIFS

SIFS is the shortest fixed IFS. It is the time space following data frame. SIFS can provide the highest priority to the frame after it. In the network, all the stations keep detecting the transmission media for the idle channel. Once the channel is sensed idle, every station should wait an additional time period before sending. The length of the additional time period depends on the function the customers want to carry on. And the functions using SIFS have the highest priority. Because the shorter the additional waiting time period is, the more likely the frame will be sent.

In the DCF, SIFS is used before ACK, between RTS and CTS in four way handshaking mechanism. In other functions, it is still used in between consecutive MAC protocol Data Unit (MPDU), before the poll response in the PCF and before any frame in the Contention Free Period (CFP). When the station get the access of the channel and wants to maintain the control to finish this transmission, it should use the SIFS, which avoid others to try to access to the channel because the SIFS is shortest.

DIFS

DIFS is the longest IFS in DCF. It is used before every attempt to send frames. All stations must sense the channel idle before its transmission. In the DCF, when a station senses the channel idle, it must first wait for additional DIFS before its attempt to access to the channel (Even the station waits for DIFS, it may not send its packet immediately. The details will be introduced in the following part). DIFS is longest to guarantee that the new attempt will not block the normal frames expected in the current transmission.

DCF Procedure

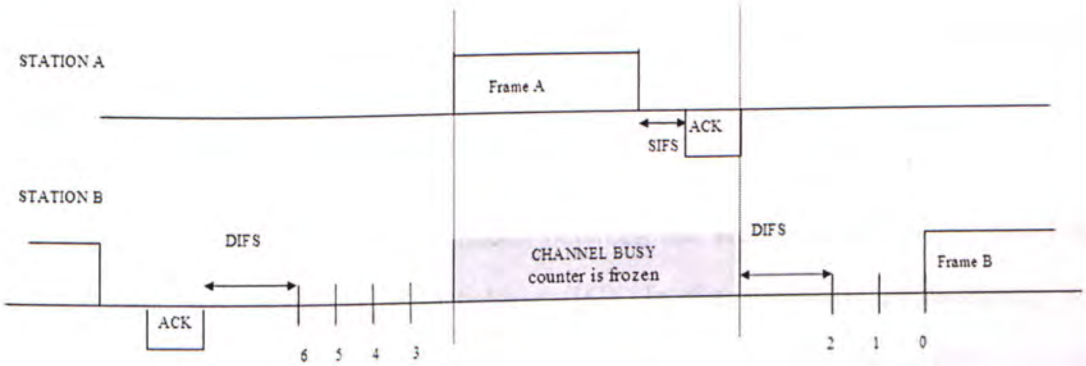

Fig. 2.2   The Procedure of DCF

The whole procedure of DCF is shown in Fig. 2.2. In the beginning, a mobile station that intends to transmit a packet should start a discrete time counter, called back-off counter. This counter decreases to take count and its starting number is randomly chosen from (0, CW-1), where CW is Contention Window (CW). When the channel is sensed idle for a time period equal to the DCF inter-frame space (DIFS), the counter will start to decrease. If the channel is continuously idle for one time slot δ, the counter will decrease one. When the channel is sensed busy, the counter will be frozen and restart to decrease when the channel is sensed idle for DIFS again. The mobile station will transmit its packets immediately when the counter reaches zero. Because the time is slotted, the counter will only be frozen in the beginning of one time slot.

In the procedure above, all kinds of IFS and length of frames have been determined before hand according the PHY property. The only one thing varies in DCF is CW. It will somehow dominate the transmission probability. CW depends on the collision number this packet has met. At the first transmitting attempt, CW is assigned the value CWmin, which is called the minimum CW. In the consecutive unsuccessful transmissions (due to collisions),

$$CW = 2^n CW_{\min} - 1 \tag{2.1}$$

where n is number of collisions, namely back-off stage. There is also an upper bound of CW,

$$CW_{\max} = 2^m CW_{\min} - 1 \tag{2.2}$$

where m is maximum back-off stage. When the number of collisions is larger than m, it still uses the CW*max*.

There are two handshaking mechanisms between the sender and receiver, two-way handshaking and four-way handshaking ([6]). In the two-way handshaking, the sender will transmit the data frame immediately if it gets the control of the transmission media. And the receiver will send back the ACK if the data frame transmission is successful. The duration between data packets and ACK is SIFS, which is shorter than DIFS to avoid any other mobile stations to transmit packet before the ACK. In the four-way handshaking, the sender will send a test short frame RTS (Request to send) before sending the data frame. If there are no other mobile stations sending packet at the same time, the receiver will receive RTS and send back a CTS (Clear to send), after which normal data frame transmission and ACK response occurs. Since collision may occur only on the RTS frame, and it is detected by the lack of CTS response, the RTS/CTS mechanism helps to increase the system performance by reducing the penalty of the collision especially when long frames are transmitted.

2.2 The Major deficiencies in the DCF

The whole procedure of DCF can be simplified as State Transmission Diagram in Fig. 2.3.

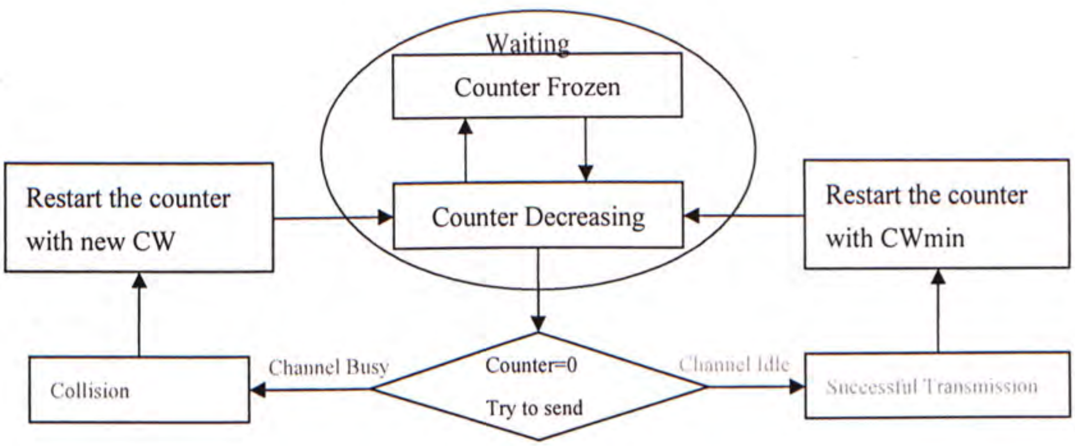

Fig. 2.3 The Simple Model of DCF

In the Fig. 2.3, we can see clearly that there are two overheads in the DCF. One is idle waiting time when the back off counter decreases. The other is the penalty of collisions when more than one station want to send their frames at the same time. Under both of the conditions, the channel is wasted for no frames are transmitted. These two overheads are derived from ALOHA system. Now all kinds of MAC protocols would like to decrease these two overheads.

When we analyze the model further, we find a balance between these two overheads. As we know, in the distributed algorithm, all stations behave under the local information. In the Wireless LAN, the local information is number of collisions the station has met and stations' behaviours are adjusting the transmission probability. Under the condition that there are fixed number of active stations in the Wireless LAN, if the stations adjust their transmission probability very high at any time slot, the idle waiting time is very short but the collisions probability is very high. Inversely if they adjust their transmission probability very low, the collision happens rarely but the idle waiting time will be too long.

In the DCF, we adjust the transmission probability by varying the CW. As we know, the time in the Wireless LAN is slotted. Every station should try to send in the beginning of one time slot. If is CW = W, the average of counter value B, E[B] is roughly equal to W/2 for the starting value of counter is randomly chosen from (0, W-1). So at any time slot the probability q that the node will send its packet is ([7])

$$q = \frac{1}{E(B)+1} \tag{2.3}$$

Besides all kinds of IFS, there are real idle time slots and transmission attempts happening. Here we also denote a kind of *virtual time slot*. The virtual time slot begins at the time point that some station's counter value reaches zero. Then the collisions or successful transmissions happen only in the virtual time slot. No matter how long the transmission attempts are, this period of time is defined as a virtual time slot.

With this idea, we can understand this formula (2.3) easily. If B = 2, it means the station should wait for two real idle time slots before sending its frames. With the last virtual time slot, the probability of transmission attempt at any time slot is 1/3.

DCF try to vary CW to adjust the q and then balance the trade off between these two overheads. However when we refer the formula (2.1), we find that CW is totally decided by the number of collisions, the transmission history in other words. But the transmission history does not have the direct relationship with the collision probability in the future attempt to send.

In fact, the factor that influences the future collision probability is the number of active nodes in the same Wireless LAN in the next transmission cycle. The more active nodes in the same cell, the higher the collision probability will be. In DCF, it tries to measure the number of active nodes by the number of collisions. When one station meets many collisions, it is supposed that there are many active nodes that want to send. In this case, it will enlarge the CW to avoid the future collisions.

However the design idea of DCF will meet two problems. First more collisions do not always mean that there are more active nodes in the Wireless LAN. It can imply that there may be many active nodes in the past. Whereas it cannot show that there must be many active nodes in future. In addition, when a frame become head-of-line first, the station will use the CW_{min} following to DCF, which is not proper. Because a former successful transmission does not show that the number of active nodes in the Wireless LAN decreases enormously. This procedure will arouse much higher collision probability.

We can give some concrete examples to illuminate this idea ([8]). In the beginning of a Wireless LAN, there are many new stations joining in. None of them has met collisions. Then all of them will use the CW_{min}. The situation is shown in the Fig. 2.4.

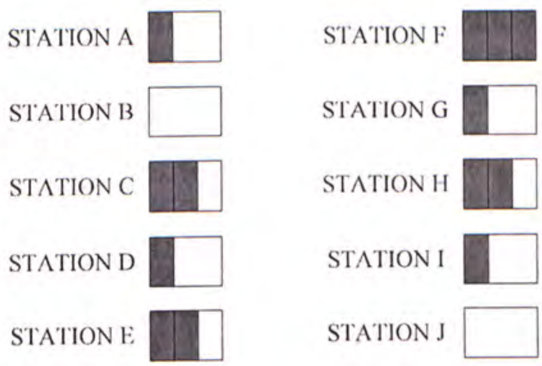

Fig. 2.4 The example 1 of inaccuracy in DCF

Under the situation in the Fig. 2.4, Station A to Station J use the $CW_{min} = 3$. Then at least Station B and Station J that choose 0, Station A, D, G and I that choose 1, and Station C, E and H that choose 2 as the counter starting value will collide with each other. Following the DCF, these stations should choose CW_{min} because they have not met any collisions. However, the CW_{min} is apparently not suitable in this case.

Another example is shown in the Fig. 2.5 ([8]), which follows the example 1.

Fig. 2.5 The example 2 of inaccuracy in DCF

After a long time, the station C to J has sent the frames successfully and maintains inactive. There are only two active stations, A and B. Whereas A and B have large counter values for many collisions in their transmission history. In this case, on the one hand no one occupies the channel. On the other hand, Station A and B should wait to access to the channel. The precious transmission media is wasted.

Besides the issues above, we find another problem in formula (2.1). In this formula, we use the binary increasing mechanism. It is actually an industrial experiential result and can not be suitable for all the conditions. It is quite easy to understand this problem. There are so many situations in the network and '2' can not be the optimized value all the time.

In the practical Wireless LAN, the whole system efficiency is only about 50%. Besides the necessary system control spending, the overheads introduced by DCF are also important reasons ([9]). The current DCF solution to these overheads is not all right through the analysis above. Especially these two problems derive from the formula (2.1) become our motivation to find a better protocol to improve the DCF.

2.3 Improvement directions

Before we discuss some solutions to improve the DCF, we should find some principles to guide our work. The first principle is simplicity. The most advantage of Wireless LAN is easy to employ. And the hardware complexity in the Wireless LAN is quite limited. Under these conditions, all stations should follow a simple algorithm to share the channel. The protocol had better absorb the distributed algorithm. Otherwise the central management algorithm will be too complicated or the overheads introduced by central management will be too high. In addition, the computation complexity should not be too high. In the Wireless LAN, we must assure that the algorithm can be finished in a certain short time and the device needed is power saving. These factors are very important for the mobile nodes.

The second principle of MAC protocol is efficiency. The MAC layer is constructed for different users to share the unique transmission media. Then the MAC protocol should guarantee that the mechanism is efficient. In other words, it should reduce the system overheads as much as possible. As we discussed before, there are two major overheads in the Wireless LAN. One is idle waiting time, and the other is penalty of collisions. What is more, there exists a trade off between these two factors. It is impossible to reduce both of these overheads at the same time. So our goal is changed to reduce the sum of these two overheads by adjusting some system parameters to optimized values.

We do not want to improve a totally new protocol to take place of DCF. That will be impractical because all the current hardware devices should be updated. And the new protocol can not be compared with the old one. As told in the second paragraph of this part, now we want to find a key parameter which will influence the overheads directly and significantly. This parameter should balance the trade off of the overheads. We have shown that the relationship constructing the trade off is the transmission probability of one station at any time slot. And in the current protocol, the parameter that will change the transmission probability mostly is the Contention Window (CW). So next we try to find a mechanism to get optimized CW to replace the formula (2.1).

Aiming at the two major deficiencies found from the formula (2.1) in the DCF, we give some proposed solutions. We choose the number of active nodes as our algorithm condition instead of number of collisions now that the former is real factor that will influence the collision probability. Secondly we abandon the binary increasing algorithm (formula (2.1)), and use the optimization method to get CW. (Besides our analysis above, in the ([9]), G. Bianchi compared all parameters and also pointed out that CW is the parameter that influences the system performance most through his mathematical analysis and simulation.)

In fact there are some researcher also arguing the assumption and mechanism of DCF and some solutions are proposed ([10] ~ [15]). For example, in some improved algorithms a busy-tone channel is added besides the data channel and then the contention information will help in the collision resolution ([10], [11]); some mortified algorithms choose different parameters in the collision resolution algorithm instead of the binary exponential back-off mechanism. ([10],[12],[13]).

But most of the dual-channel algorithm meets the following problem. The hardware complexity is too high and the spectral efficiency is low. Because the bandwidth of the feedback channel should be divided from the data channel and the interval bandwidth is needed, even through they are narrow-band. What is more, an additional receiver is listening in the busy channel and a sharp cut off band-pass filter is indispensable. Although some researchers said that we can use the nulls in the power spectrum of the data modulation to transmit the feedback signal ([14]), it will bring more corporation complexity of the MAC layer and PHY layer and call for complicated modulation technology. It actually brings the MAC difficulties to the PHY layer.

Dynamic adjusting the contention window factors is mainly based on the estimation of the number of the active stations in WLAN. But they did not provide an efficient way to estimate the accurate value of optimized system parameters. All the values are derived from the simulation results and practical experience.

In the end, we propose our MAC protocol based on the analysis above and others' work.

CHAPTER III

Proposed MAC Protocol

Abstract

In this chapter, we will introduce the details of our proposed MAC protocol. Based on the deficiencies of DCF, we give some valuable solutions. In addition, we design a new mechanism for the infrastructure network. These are our major contribution.

- The Design Idea

  In this part, we first introduce our basic idea of the proposed MAC protocol. Secondly we divide our work into three parts, whose details will be introduced in Chapter 3.2, 3.3 and 3.4.

- The Number of active nodes

  In this part, we will introduce the method to get the number of active nodes in the Wireless LAN at real time. This is a very important parameter in our method. It contains two parts: one is deterministic part, and the other is the probabilistic part.

- Optimization Method for CW

  In this part, we will give the optimization for CW based on the information we get from the previous part. We analyze the CW from the basic queuing model and find the direct relationship between CW and two overheads. Then the optimized CW is derived by minimizing the sum of the system overheads.

- CW and Counter value Updating

When the optimized CW is derived, all stations should update their local CW. In this part, we will introduce the ways for CW updating and how to renew the counter value according to the novel CW.

- Procedure Flow and Simulation Results

  Based on the details introduced above, we will give the whole procedure flow in this part. The proposed MAC protocol does not call for the hardware updating, but just needs some software renewal. In the end we give some simulation results to validate our analysis.

3.1 The Design Idea

As we discussed before, currently in the Wireless LAN, DCF uses the distributed algorithm. However the distributed algorithm has its unconquerable disadvantage. All the stations determine their sending probability just according to local information or the transmission history. It is design to implement simply but the efficiency is too low. Of course, it is impractical to use central control algorithm to totally replace the distributed ones. But we can combine them together to get more credits. We also absorb the distributed algorithm but import some global information to improve the performance.

Fortunately in the infrastructure network, which is employed mostly, it is not difficult to get partial global information. In the infrastructure network, there always exists an access point (AP). And all the stations incorporate under the control of the AP. They should get the admission of AP before entering the WLAN. Still they should forward their frames to AP no matter the destination is in the same cell or not. Then the stations could notify the AP whether it still has data to send after this transmission. The procedure is shown in the Fig. 3.1.

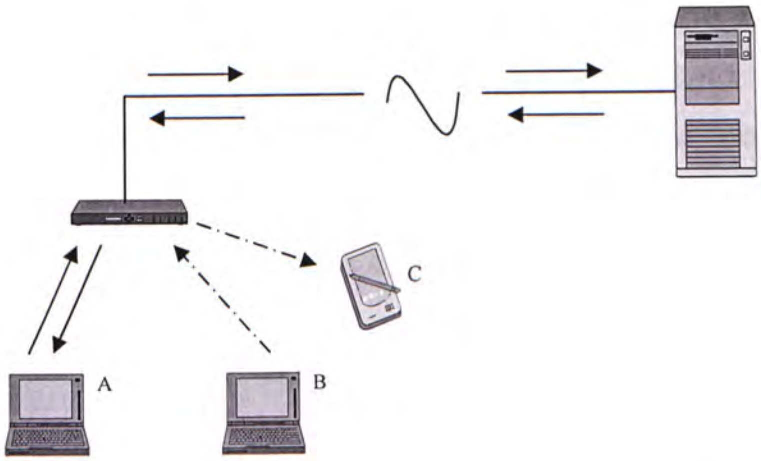

Fig 3.1 The communication measure in the Infrastructure network

As shown in the fig. 3.1, no matter station A needs service from the remote server or station B and C want to communicate with each other in the same LAN, they all must send their frames to the AP first. AP knows every detail of transmissions in the Wireless LAN.

In this case, AP can easily collect the distributed information and then gets the number of the active mobile stations in the next contentions cycle. Then AP can follow some optimization method to get the proper CW in the next cycle. It will broadcast the latest CW when necessary through the current frames. When other stations receive the new CW, they can adjust their current counter value according to the new CW they received.

We can divide our work into parts. In short words, there are three steps in the proposed MAC protocol.

1. We should get the number of active nodes in the Wireless LAN;
2. CW is derived from the optimization method.
3. All the stations should update their counter values.

3.2 The Number of active nodes

As we discussed in Chapter 2.2, the number of active nodes in the next contention cycle is the direct factor that will influence the future contention probability. So we should find this crucial parameter as our optimization condition instead of the transmission history.

When one station send its frame to the AP, the frame structure will be changed a little as in Fig. 3.2 .

	FC	Duration	Addr 1~3	SC	Addr 4	Symbol	Data	FCS
No. of Bytes	2	2	18	2	6	1	0~2312	4

Fig. 3.2 The Frame Structure of common stations in the Proposed MAC Protocol

One additional byte is inserted into the original frame structure. It is used to notice the AP whether the station has frames to send after this one.

In fact one bit is enough and we can also use the reservation bits in FC (Frame Control). We add one byte here in order not to influence the current and future functions. And we can compare the proposed protocol with the current one.

From the Fig. 3.2 we can see that the overhead introduced by the proposed protocol is very limited, however the performance improvement will be very obvious.

Through the method above we can know the nodes active if they still have frames to send after this one. They are deterministic part. Whereas there is another part we cannot know whether they are active or not in the future. We call them probabilistic part.

After the last successful transmission, the station notice AP that its queue has been empty. However after a certain period, there may be some new packets coming to the station queue. These stations are transmitting from state 'Inactive' to state 'Active'.

There is no way for them to notice AP that they have been active again unless we add some additional control frames. However if we do construct more control frames, the whole protocol will be too complicated and the overheads introduced by the proposed protocol will be too high. On the other hand, because the stations should contact with AP termly for some other functions (please refer to [1], [2] for the details of MAC functions), they always have the opportunity to notice the AP the state transmission. So the probabilistic part influence is not very evident. In the end, we will use prediction algorithm to get the number of this part.

Suppose there are totally *N* stations in the Wireless LAN. N_1 stations belong to the deterministic part and then $N_2 = N - N_1$ belongs to the probabilistic part. Now we consider some station *i* belonging to the probabilistic part. The time from its entering this Wireless LAN to its last successful transmission is T_i; and at this period it has sent m_i packets, which also means that there comes m_i packets in the this station. Without any more information, we can only suppose the arrival process is the simplest linear stochastic process, which is Poisson Process. In this case, the arrival rate is $\lambda_i = m_i / T_i$.

We also denote time t_i from the station's last transmission to the current time point. Then we know that the probability p_i that the node is active is

$$p_i = 1 - e^{-\lambda_i t_i} = 1 - e^{-\frac{m_i}{T_i} t_i} \tag{3.1}$$

The assumptions are shown in Fig. 3.3.

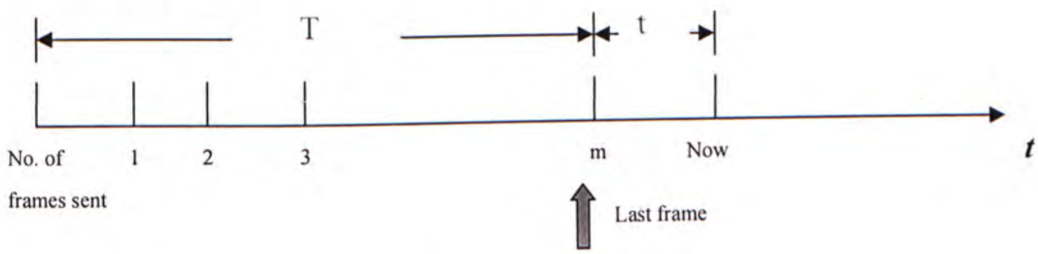

Fig. 3.3 The Prediction for the probabilistic part

In this case, the total number of active nodes in the next contention cycle is

$$n = N_1 + \sum_{i=1}^{N_2} p_i = N_1 + \sum_{i=1}^{N_2} (1 - e^{-\frac{m_i}{T_i} t_i}) \tag{3.2}$$

3.3 Optimization Method for CW

When the AP gets the number of active nodes in its Wireless LAN, it will derive the optimized CW.

From the view of basic queuing model, the behaviour of one station can be shown as Fig. 3.4. The only difference is that the server may be occupied by others. (In fact it can be viewed as the *vocation model.*) Our goal is to find efficient MAC protocol. That will incarnate the service rate or the service time of one customer. So we should find the way to shorten the service time availably by choosing the optimized CW.

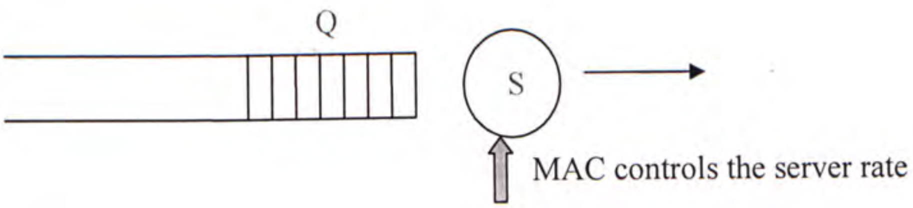

Fig. 3.4 The queue model of one station

By observing the transmission behaviours in the wireless channel, a pattern of period cycle can be found ([16]). It is the "service time" of one frame as in Fig.7, which starts at the time when a new frame becomes head-of-line and ends at the time when it is successfully transmitted. We call it "transmission cycle".

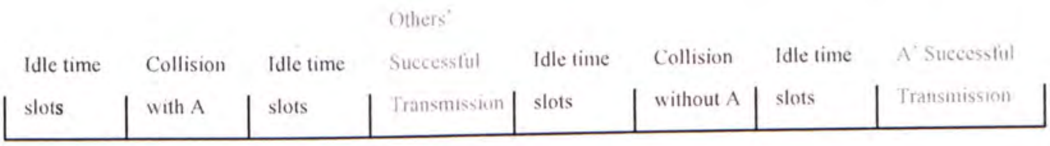

Fig. 3.5 The construction of a transmission cycle

As shown in the Fig. 3.5, from the view of a said node A without loss of generality, if we consider the usage of the wireless channel in a transmission cycle, it can be divided into five parts.

1. Idle time slots; (We also denote it as a kind of channel usage because although it is not actually used, the channel resource is also lost without transmitting packets.)
2. Penalty of collisions that do not involve node A;
3. Penalty of collisions that involve A;
4. The successful transmissions of other nodes;
5. A's successful transmission.

A's transmission cycle must end with its successful transmission. And the former four parts in a transmission cycle exist with some probability.

In the view of protocol efficiency, these five above parts can be sorted into two categories. The first category, called "payload", is the successful transmissions, which can't be shortened. The second one, called "overhead", is the idle time slots and collision time period, which waste the channel resource and must be shortened to improve the protocol efficiency. In the proposed protocol, our goal is to heighten the efficiency by reducing the overhead.

In the standard protocol, both these overheads are influenced by CW. So next we would like to find the direct relationship between the CW and two overheads. Then CW can be derived by minimizing the overheads.

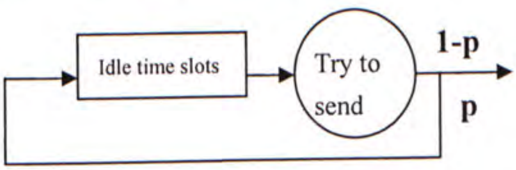

Fig. 3.6 The server model

The model of server in the Fig. 3.4 is shown in the Fig. 3.6. Suppose that at each transmission attempt, every packet has the common probability p of involving in collision when it is being transmitted, where p is independent of retransmission history [9]. Suppose we choose the CW = W, then p with q in the formula (2.3) is,

p = Prob [A tries to send & others tries to send | A tries to send]

$$\begin{aligned} p &= \frac{q(1-(1-q)^{n-1})}{q} \\ &= 1-(1-q)^{n-1} \end{aligned} \tag{3.3}$$

where n is number of active nodes gained in the previous chapter.

In a transmission cycle, which ends at a successful transmission, the distribution of the number of retransmissions is geometric with parameter (1-p). Then, the number of idle time slots Λ is (Notice: *E(B) = W/2*),

$$\Lambda = E(B) * \sum_{i=0}^{\infty}(i+1)p^i(1-p) = \frac{W}{2(1-p)} \tag{3.4}$$

Then the first kind of overhead caused by the idle time slots in a transmission cycle is $\Lambda * \delta$, where δ is the length of one time slot.

For the second kind of overhead, first suppose that the probability P that there happens a collision in a time slot, no matter it involves A or not, is

P = Prob [More than 1 stations try to send]

$$P = 1-(1-q)^n - \binom{n}{1} q(1-q)^{(n-1)} \tag{3.5}$$

With the concept *virtual time slot* introduced in Chapter 2.2, we can find the number of collisions Δ in one transmission cycle is

Δ = (Real Time Slot + Virtual Time Slot) * P

$$\begin{aligned} &= (\Lambda + \Delta + n) * P \\ &= \frac{P}{1-P}\left(\frac{W}{2(1-p)} + n\right) \end{aligned} \tag{3.6}$$

Because all the active stations have the same priority, the mean of successful transmissions in one transmission cycle is *n*.

Suppose we use four way handshaking mechanism in the protocol, and then the penalty of one collision is $T = (RTS + DIFS)$. Here *RTS* and *DIFS* mean the time length of corresponding frame and IFS. Then the second kind of overhead caused by collisions is $\Delta * T$.

Finally we find the close form of the sum of two overheads Ж and CW as below:

$$Ж = \Lambda * \delta + \Delta * T$$

$$= \frac{W}{2(1-p)}\delta + \frac{TP}{1-P}\left(\frac{W}{2(1-p)} + n\right) \qquad (3.7)$$

Then we can find the optimized W by minimizing Σ following to any *n*.

3.4 CW and Counter value Updating

When the AP calculates out the optimized CW, it should notice all the stations when necessary. As discussed before, all the stations are able to contact with AP whenever they are in the Wireless LAN. So they must keep in the transmission area of AP, therefore they cannot be hidden terminals to AP. In other words, AP can notice other stations whenever it would like to.

Essentially we can design new frames for the CW broadcasting. However it is not very necessary. We can adjust the frame structure of ACK to carry our information.

	FC	Duration	Addr 1~3	SC	Addr 4	CW	Data	FCS
No. of Bytes	2	2	18	2	6	2	0~2312	4

Fig. 3.7 The Frame Structure of AP in the Proposed MAC Protocol

The new frame structure of ACK is shown in Fig. 3.7. We add a two bytes domain containing the latest CW. Normally there are less than 1000 stations in one cell. It is enough for 2 bytes to denote the new CW value. Because every transmission from common stations to AP needs an ACK, AP can broadcast the latest CW through ACK with the new frame structure above.

Certainly sometimes AP sends data packets to common stations and the latter send back the ACK. In this case, AP also inserts 2 bytes domain as Fig. 3.7 instead of the symbol byte in the Fig. 3.2 to broadcast the latest CW. And the common stations will follow the Fig. 3.2 to construct the ACK frame structure to notice AP whether they are active or not after this successful transmission.

When the common stations receive the novel CW value, they should store it for new counter starting value selection. Besides, they should also adjust their current counter value as well. This can guarantee that the overheads will be shortened as much as possible.

However for fairness the nodes cannot randomly choose a new counter value again after adjusting the CW. Otherwise, the old transmission sequence may be changed. For example, Station A started its back off counter as "9", and the counter reaches "3" after waiting 6 time slots. Station B started its counter as "8" and the counter reaches "7" after waiting one time slot. A will try to send before B in the old sequence. However now the new CW = 15 is received and both A and B choose the starting value again. A selects "10" and B selects "4". A arranges after B after this adjusting, which is not fair for A.

So we map the old counter value to the new one following the below rules:

1) The old sequence won't be changed for fairness;

2) The distribution of the counter value with the new CW is uniformly distributed, which will reduce the probability of collisions.

Under these two rules, we use the linear extension or compression. Denoting the old counter value and contention window are separately b and w, and the new ones are B and W, then

$$B = b*W/w \tag{3.8}$$

3.5 Procedure Flow and Simulation Results

Based on the discussion above, we give the whole procedure flow figures as below. Fig. 3.8 shows the sending procedure of the common stations. Besides adjusting the data frame structure, they should still receive the ACK from AP no matter the ACK is sent to them or not. If the new ACK containing the latest CW is received, the common stations will rectify the counter value following to the algorithm in Chapter 3.4. We must point out that the stations that even meet collisions will use the same CW unless they are told to change it by AP. When AP wants to send data frames, it will follow the Fig. 3.8 too. The only difference is that now AP holds latest CW itself other than receiving from ACK.

The receiving procedure of AP is shown in Fig. 3.9. When AP receives the frames from the common stations, it will calculate the optimized CW based on the global information it has gained. If the CW value changes, AP will notice the common stations through ACK.

The receiving procedure of common stations is shown in Fig. 3.10. When the common stations receive the data frames from AP, it will get the latest CW meanwhile. Then it can adjust its counter value and send back ACK containing the local information. (Notice: Some stations belonging to probabilistic part can notice AP whether they are active in this way.)

Sending Procedure of common Stations

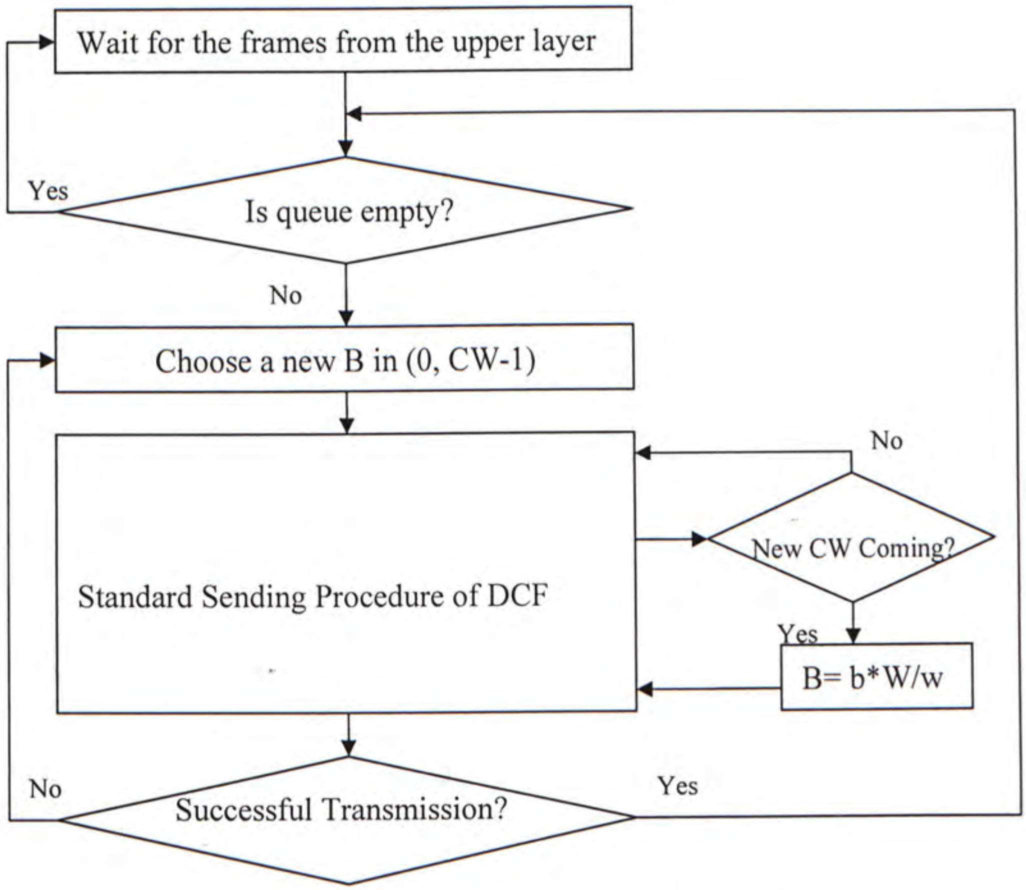

Fig. 3.8 The Sending Procedure of Common Stations

Receiving Procedure of AP

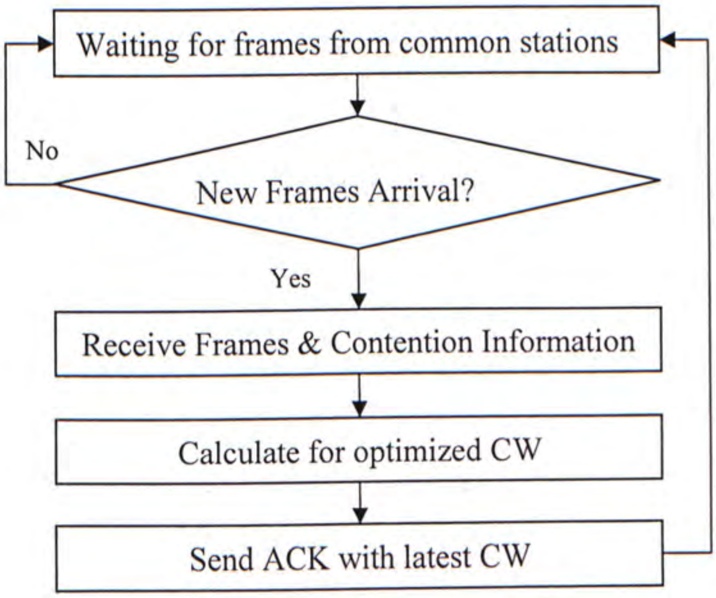

Fig. 3.9 The Receiving Procedure of AP

Receiving Procedure of common stations

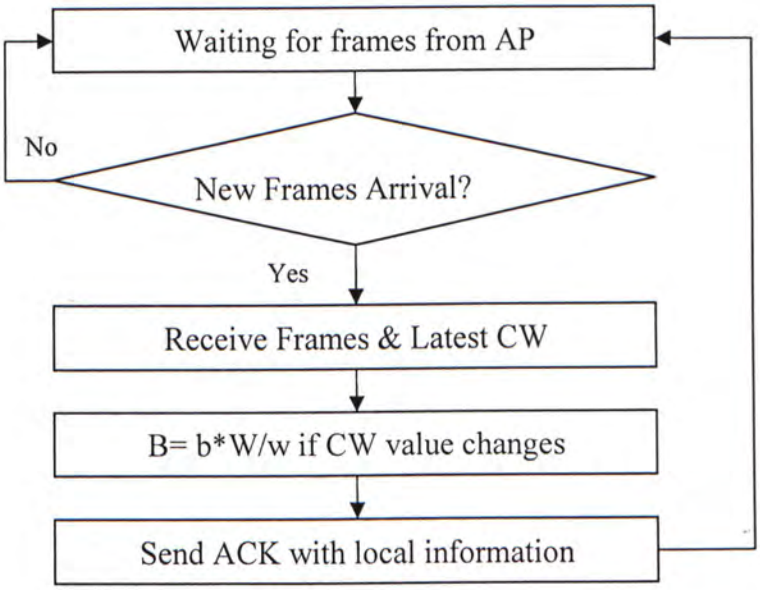

Fig. 3.10 The Receiving Procedure of common stations

Besides the analysis above, we present the detailed simulation studies for the proposed protocol compared with the IEEE 802.11 MAC protocol in a wireless LAN. We validate the analytical model by using the *Matlab* 6.5 and *ns-2* simulator ([17]). All values of the parameters in the simulation are shown in the Table 3-1, which are assigned according to the IEEE 802.11 specification ([1], [2]) and some proper simulation environment ([18]). And the arrival process is EXPOO_Traffic ([17]). For the simulation efficiency and simplicity, the average channel rate bit rate is 10 Mbps, the data length is 1000 bytes and we use the four-way hand shaking.

Table 3-1 The Simulation Parameter Values

Parameters	Values
PHY header	6 bytes
MAC header	36 bytes
RTS	30 bytes
CTS	14 bytes
ACK	16 bytes
DIFS	50 us

SIFS	10 us
Slot Time	20 us
Propagation Delay	1 us
Average bit rate	10 Mbps
Channel bit error rate	10^{-5}

In these Figures, besides the IEEE standard protocol lines and the proposed MAC protocol lines, we drew an additional line called "Pure payload bound-line", which means there are no idle time slots and collisions. This line is a bound line for us to reach, but can not be surpassed. It is compared with other two lines to show how much the proposed protocol reduces the overhead. In addition, the delay has been normalized by the packet transmission time.

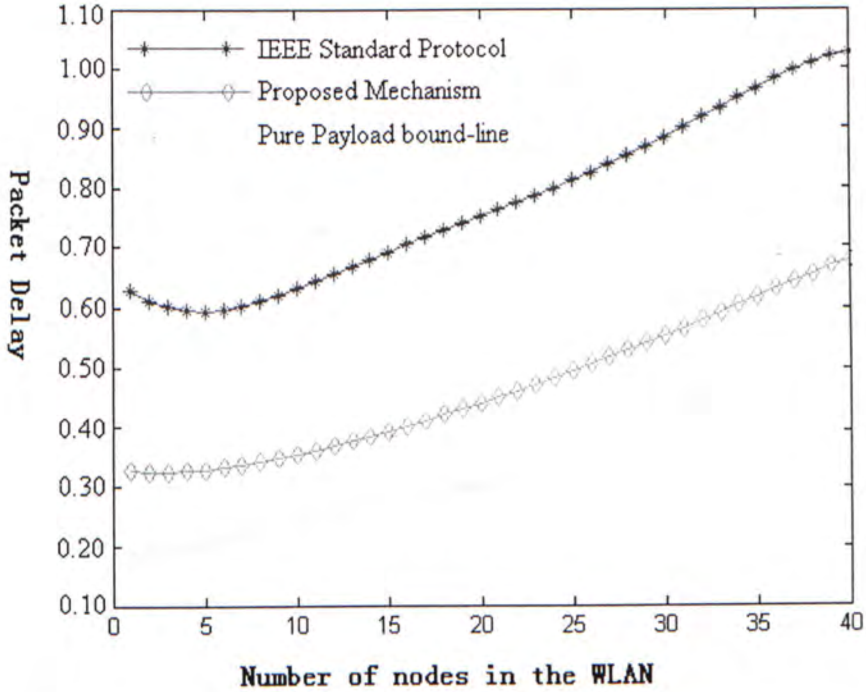

Fig.3.11 (a) Packet Delay VS. number of nodes in the WLAN

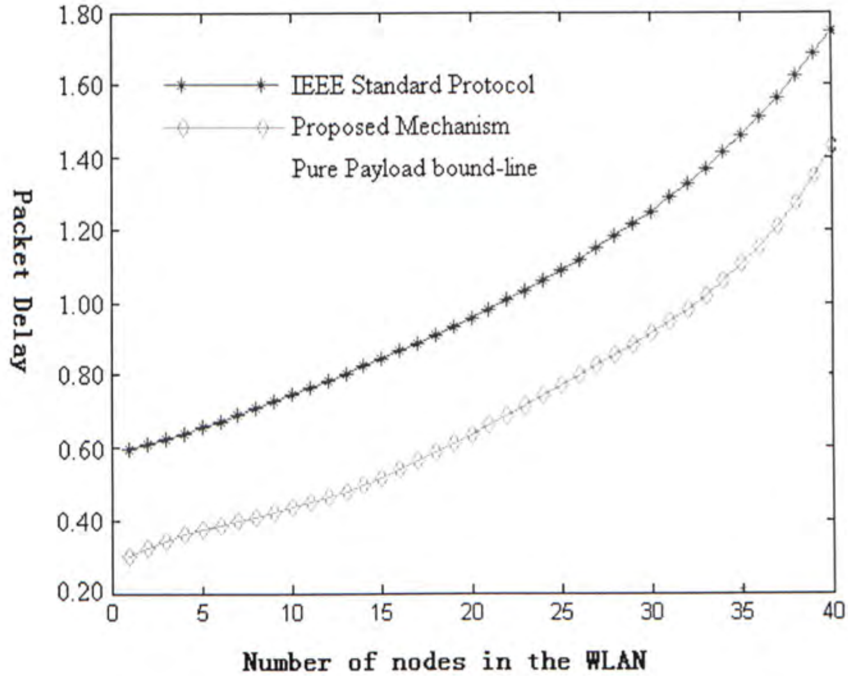

Fig.3.11 (b) Packet Delay VS. number of nodes in the WLAN

Fig. 3.11 shows the average packet delay versus the different number of nodes in the WLAN. Fig. 3.11 (a) is based on the packet rate 2.5 Fbps and Fig. 3.11(b) is based on the 4 Fbps. From these Figures, we can see clearly that the proposed strategy can consumedly reduce the packet delay.

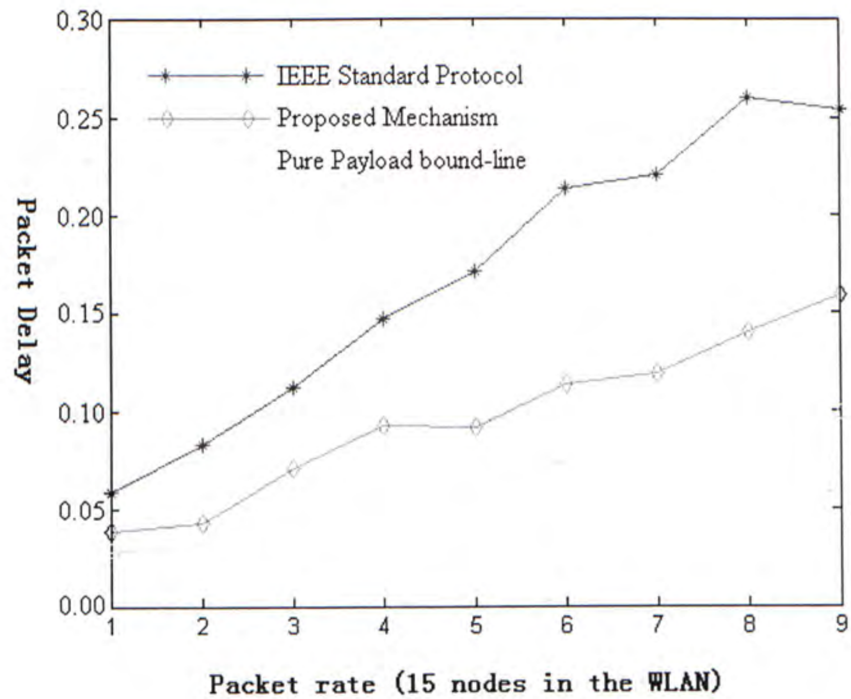

Fig. 3.12(a) Packet Delay VS. offered load (15 nodes in the WLAN)

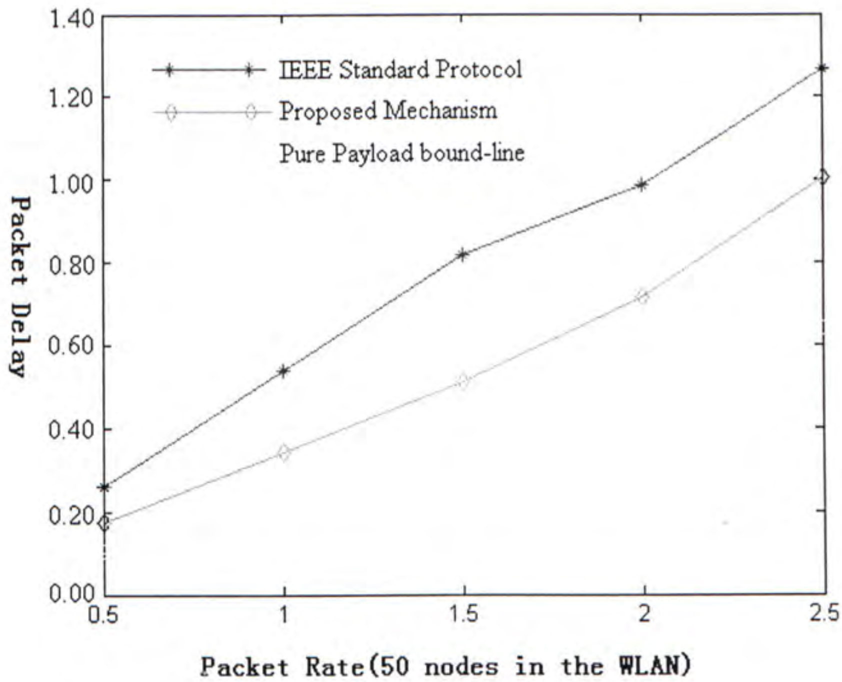

Fig. 3.12(b) Packet Delay v VS. offered load (50 nodes in the WLAN)

Fig. 3.12 shows the average packet delay versus the different offered load rate. There are 15 nodes in the simulation of Fig.13 (a) and 50 nodes in that of Fig. 13(b). In most of our simulation scenarios, over 50% of overhead is reduced by the BC strategy.

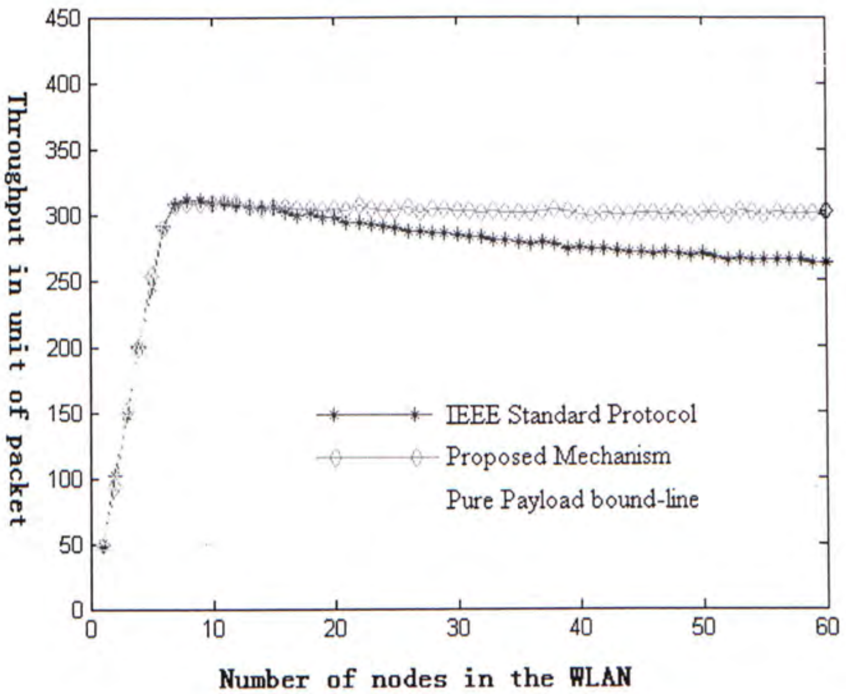

Fig.3.13 Throughput VS. number of nodes in the WLAN

Fig.3.13 shows the throughput versus the different number of nodes under a saturated offered load. The IEEE 802.11 MAC works well for the low offered load and small number of nodes. However when the offered load of the whole network is increasing, the performance will deteriorate quickly. But for the proposed protocol, the throughput will maintain the same level regardless of the number of active nodes in the network even when the offered load is very high.

Based on all the discussion in this chapter, we introduce a novel MAC protocol to solve the problems in the DCF. The analysis and simulation results have shown that our new protocol have much higher efficiency than the IEEE 802.11 protocol.

CHAPTER IV

Advanced Proposed Protocol with QoS issues

Abstract

The QoS has been the future requirements of Wireless LAN. In this chapter, we will introduce the advanced proposed protocol to support QoS issues. The advanced proposed protocol follows the basic mechanism in the previous chapter but designs a new algorithm to provide service differentiation.

- QoS requirements, EDCF solution and others' work

  In this part, we briefly show the QoS requirements in the Wireless LAN. Secondly, we introduce the Enhanced Distributed Coordination Function (EDCF) and its suggested solution to service differentiation. In the end we review others' work on this problem.
- Frame structure changes in the Advanced Proposed MAC Protocol

  In fact, we can almost follow the procedure introduced in chapter III. However the former proposed protocol is designed for one queue service but here different traffic classes consist of different queues. In this part, we will introduce the frame structure changes compared with that used in Chapter III.
- Recursive Balance Optimization Method for CW

  In the optimization algorithm introduced in Chapter III, one optimized CW is derived. But now distinct CWs realize different priorities. Then in this part, we use recursive balance optimization method to produce different proper CWs.
- Decision Algorithm

This part is actually the supplement to chapter 4.3. For the simplicity, in the recursive optimization method, we just introduce the rough structure to look for the different optimized CWs. In addition, we will concretely explain the one step decision algorithm.

- Model Validation and Simulation Results

  In this part, we use the simulation to validate our analysis result in the former parts. Besides the result diagrams, we give some necessary illumination.

4.1 QoS requirements, EDCF solutions and others' work

Recent development in the Wireless LAN has requested IEEE 802.11 protocols to offer high-speed data services. At present the rates of wired LAN have reached 10M~100M bits bps. If we want to employ Wireless LAN on a large scale, we should improve the Wireless LAN to the same or similar standard.

However, the Wireless LAN has its insurmountable disadvantage for its transmission media. The signal will be interfered and distorted badly in the channel compared with that in the wired LAN, which largely limits the transmission rate. Hence, traffic classes with different QoS requirements will be provided in future Wireless LAN.

In the future Wireless LAN, all the frames from the upper layers will be sorted to different traffic classes according to their time-bounded service requirements. Some time sensitive services (e.g., VoIP or video-conference) call for very small delay and meanwhile can tolerate high bit error rate. On the other hand, other services (e.g. Email or Certification file) care little of delay but need very small bit error rate. These service will be given different priorities to guarantee that their delay-sensitivity and bandwidth. So it is desired to provide a service differentiation mechanism in the MAC protocol.

Recently the IEEE 802.11 has specified a distributed access approach, called EDCF (Enhanced Distributed Coordination Function), to support service differentiation in the MAC layer ([19]). It ensures that the packets sent by each mobile station can be differentiated by assigning distinct access parameters.

EDCF introduces the concept of access categories (ACs), which are variants of the DCF access mechanism. Different ACs use distinct values of arbitration IFS duration (AIFSD), CW_{min}, and CW_{max}. Traffic with smaller values of CW_{min}, and CW_{max} yield higher priorities. Furthermore, different IFSs can be used by different traffic classes. DIFS (DCF Inter-Frame space) is substituted for the AIFSD. AIFSD is at least the duration of SIFS plus one slot time and can be enlarged individually by different traffic classes.

$$\text{AIFSD} = \text{SIFS} + \text{AIFS} \times \delta \tag{4.1}$$

where AIFS is a positive integer which is no less than 1. Hence, AIFS is determined by AIFS and traffic classes with smaller values of AIFS also yield higher priorities.

In short words, we assign different AFIS, CW_{min}, and CW_{max} to different traffic classes. The smaller these system parameters are, the higher priority this classes will have. But the differentiating the initial window size is better than differentiating the IFS in terms of total throughput and delay ([20]).

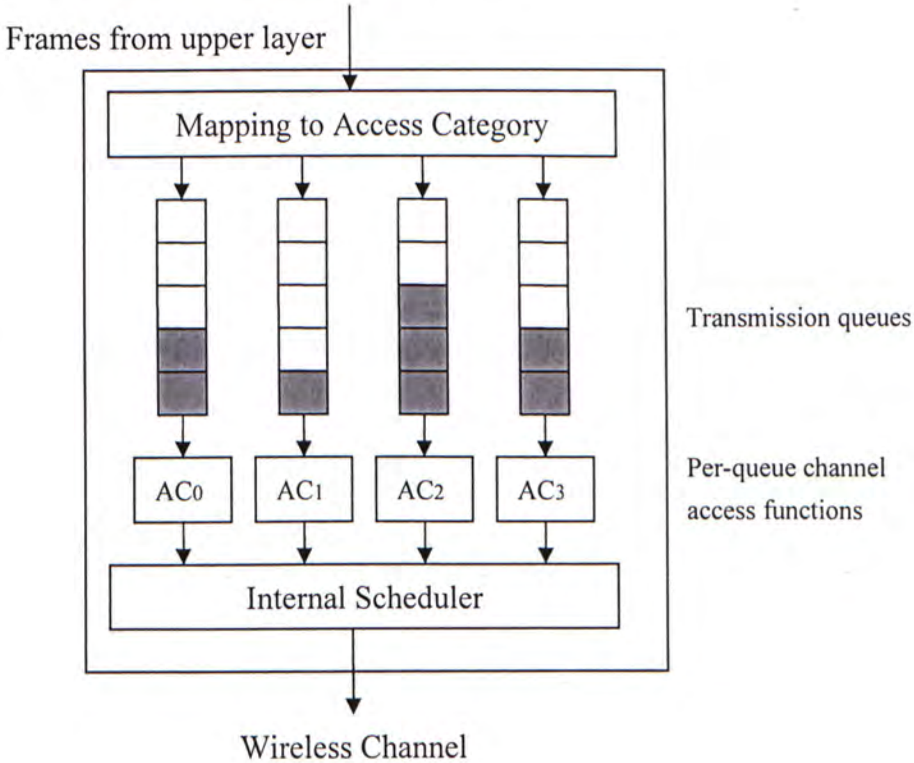

Fig. 4.1 The mobile station with four transmission queues

In EDCF, data frames are delivered through multiple back-off instances within one mobile station. A single mobile station may implement up to 4 (There are four default traffic classes in the IEEE 802.11) transmission queues and each transmission queue uses a specific AC for contending the channel access, as illustrated in Fig. 4.1. Each queue within the mobile stations contends for the channel access and independently starts its back-off procedure as in the EDCF depending on its associated AC. If the back-off time counters of two or more parallel queues within a single mobile station reach zero at the same time, an internal scheduler will resolve this kind of collisions. The scheduler grants the channel access to the queue in terms of its particular scheduling algorithm.

Based on the EDCF solution to the QoS requirements, there are still some researchers concerning on this problem ([21]~[26]). However it does not provide a concrete analysis and the model is validated by the simulation results in [21]. The authors of ([22]~[25]) proposed many methods to adjust the values of CW_{min} or CW_{max} according to the application requirements and channel conditions. But it still uses the exponential mechanism in EDCF, so the whole effect is quite limited. In ([26]), it claims to find an experiential algorithm but there is no analysis proof.

4.2 Frame structure changes in the Advanced Proposed MAC Protocol

The proposed MAC protocol introduced in the Chapter III is almost suitable for the multiple traffic classes' service except some changes.

First when the common stations send their frames, we use the same frame structure in the Fig. 3.2. However here *n* bits in the "Symbol" byte will be used to notice AP whether *n* queues are active or not after this transmission. (Normally there are less than 8 traffic classes in the Wireless LAN; otherwise the service differentiation is too complicated and unnecessary.) Therefore if a station communicates with AP once, it can notify AP the four-queue conditions no matter which queue the transmission happens to.

Second, the frame structure used by AP is different compared with Fig. 3.7. It is shown in Fig. 4.2.

	FC	Duration	Addr 1~3	SC	Addr 4	CW	Data	FCS
No. of Bytes	2	2	18	2	6	n~$2n$	0~2312	4

Fig. 4.2 The Frame Structure of AP in the Proposed MAC Protocol

There are n traffic classes in the network, so AP should find n proper CWs. In this case, there should be a multi-bytes domain to carry these values. As we know, the category with higher priority uses the smaller CW_{min} and CW_{max} and inversely the one with lower priority absorbs the bigger ones. Therefore the numbers of bytes to load these distinct values are also different. The length of bytes for each queue depends on the scope of the CW. For example, in the IEEE standards, the CW range for the category with the highest priority is (4, 8) and that for the category with the lowest priority is (16, 1024). So it is enough to assign one byte to the former and the latter needs two bytes at least. Commonly there are n~$2n$ bytes in this domain, e.g., according to the current IEEE standards, there are 6 = 1+1+2+2 bytes for the four default queues

4.3 Recursive Balance Optimization Method for CW

Besides the frame structure changes, there is also a crucial problem in advanced proposed MAC protocol. There is only one optimized CW derived in Chapter III.

However we must find the algorithm to find the n proper CW now. In fact this is the Multiple Objective Optimization. There are n variables belonging to different scope and we should find n proper values for them.

The computation complexity is supposed to be a little high and the algorithm will be too complex, which is not proper in the Wireless LAN. So we find a recursive balance method to update CW and then find the n values we need.

The basic idea is very simple. In the former optimization, we get the CW without any constrains. That result is the real optimized value. But it may not be used by many categories for the optimized CW value is out of their CW range. For example, we get the optimized CW = W_0 and

$$\begin{cases} W_0 < CW_{\min} J_0 \\ W_0 > CW_{\max} I_0 \end{cases} \quad (I_0 < J_0) \tag{4.2}$$

where $CW_{\max} I_0$ and $CW_{\min} J_0$ separately mean the CW*max* of category I_0 and CW*min* of category J_0. (Category I_0 has higher priority than category J_0.) In this case some categories should use their CW*min*, but other categories have to use CW*max*. Our design idea is to balance the influences of these categories that cannot use the optimized CW. For instance, we wan to give 100 apples to 25 persons, proposed 4 for each. However 5 men need 6 apples at least and other 10 children can eat 2 apples at most. Then on this condition, the others can get 5 apples, which is the result derived by balancing the influences from the categories that cannot use the proposed value. In short words, our algorithm is recursive balance.

The whole algorithm will be introduced in this part and Chapter 4.3. We will give the whole structure in this part. This is a binary decision tree that balances the influences and finds n proper CW values to minimize the system overheads. In Chapter 4.3, we will introduce the decision algorithm used in the root of any two subtrees.

Without loss of generality, we assume that there are L traffic categories. Specifically there are $\vec{n} = \{n_0, n_1, \ldots n_{L-1}\}$ service queues in the Wireless LAN, where $n_l (0 \le l \le L-1)$ means the number of service queues that generate traffic category l packets. And the smaller l is, the higher priority traffic category l has. For description simplicity, we suppose N is the total number of active queues:

$$N = \sum_{j=0}^{l-1} n_j \tag{4.3}$$

Firstly, we suppose all the N queues have the same priority. Following the algorithm in the former chapter, we can get the optimized CW = W_0. Unfortunately W_0 may not be proper for all the queues. We suppose the non-coincidence is as formula (4.2). And

$$\begin{cases} D_1 = \sum_{i=0}^{I_0} n_i \\ D_2 = \sum_{j=J_0}^{L-1} n_j \end{cases} \tag{4.4}$$

In the current protocol design, there is always no overlap between the ranges of different categories. The model can be shown in Fig. 4.3.

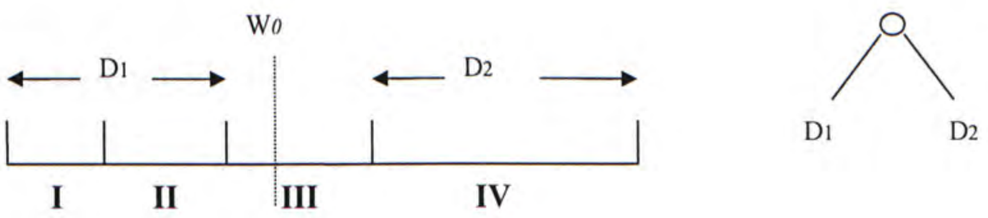

Fig. 4.3 The Recursive Method to find *n* proper CW (1)

There are two parts in the Fig. 4.3. The left part shows the CW ranges of categories I to IV and the position of W_0. D_1 and D_2 are defined as formula (4.4) and now $I_0 = J_0 - 2$. They are the parts that cannot use W0. The right part is the corresponding binary decision tree. The circle in the root is the decision algorithm, which will be introduced in the next chapter.

If $D_1 \le D_2$ (We just explain this condition as an example.), D2 is supposed to have more weights to influence the position of W0 and then the part of D2 will use their CW*min* separately! (Notice: Here we suppose D2 have more weights but it does not absolutely.)

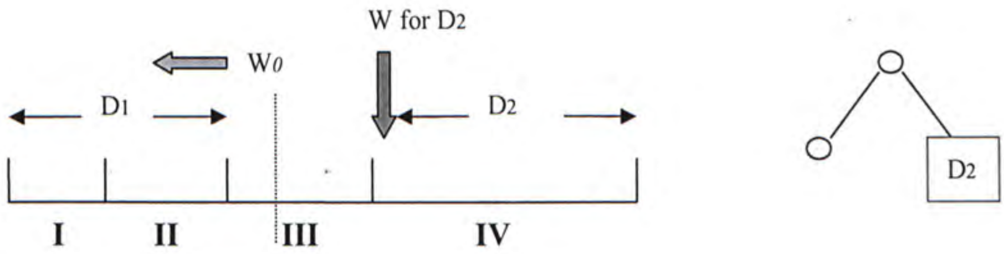

Fig. 4.4 The Recursive Method to find *n* proper CW (2)

In this case our problem changes from multiple objective optimization to conditional optimization. The part of D2 has chosen their CW already. And all the categories except D2 will choose their CW under this condition. We use the recursive method. We suppose all the categories except D2 have the same priority and then get the new optimized CW = W1 following the conditional algorithm introduced in the next chapter. Because the part of D2 uses the CW bigger than W0, the W1 will be smaller than W0 to balance the influence of D2. Suppose

$$\begin{cases} W_1 < CW_{\min} J_1 \\ W_1 > CW_{\max}(J_1 - 2) \end{cases}$$

There are two cases for the position of W.

1. $J_1 < J_0$.

It means that W_1 goes across another bound line in the Fig. This case is shown in Fig. 4.5.

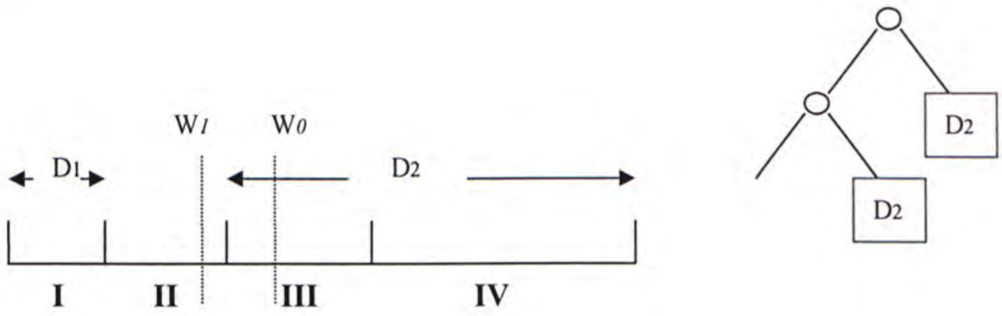

Fig. 4.5 The Recursive Method to find *n* proper CW (3)

Then we enlarge the part of D2 As shown in the fig. 4.5 and follow the same recursive algorithm to continue our procedure.

If this case goes on to the end, the situation is shown as Fig. 4.6.

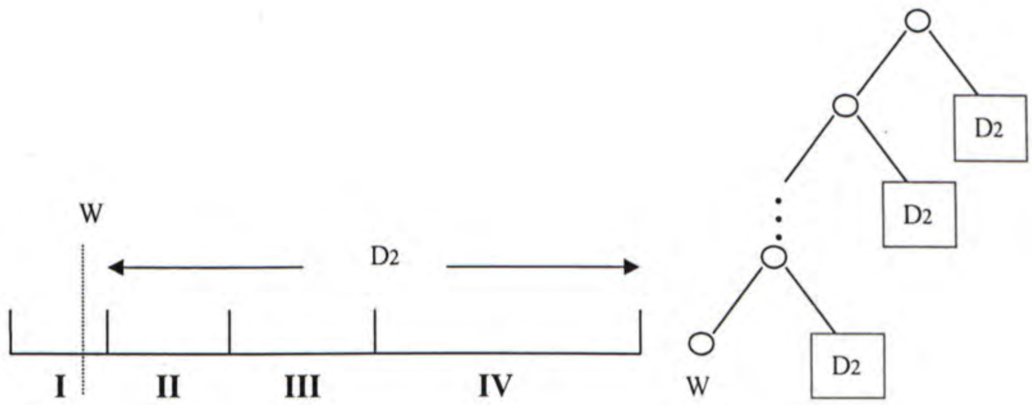

Fig. 4.6 The Recursive Method to find *n* proper CW (4)

In the end, all the categories except category 0 use their CW_{min} separately and category 0 uses the proper W.

2. $J_1 = J_0$

In this case, besides the D2, D1 cannot use the W either. We assign D1 CW_{max} separately as in Fig. 4.7.

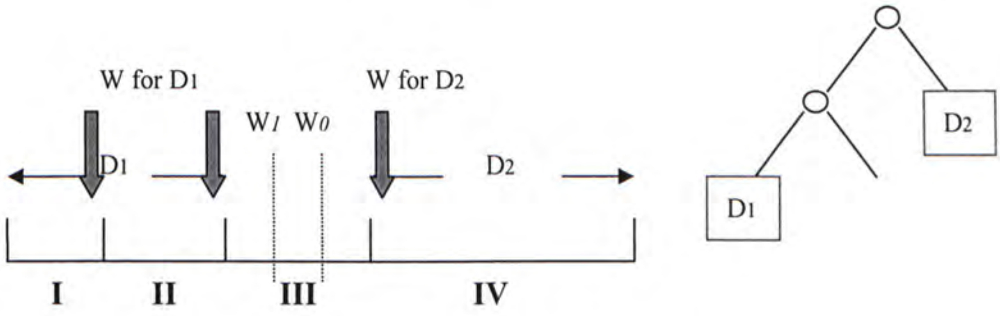

Fig. 4.7 The Recursive Method to find *n* proper CW (5)

Based on these two conditions of D1 and D2, we use the conditional algorithm to find the proper W for the middle category. For the same reason, the new W will be bigger than W1. Suppose

$$\begin{cases} W < CW_{\min} J \\ W > CW_{\max}(J-2) \end{cases}$$

If $J = J_1$, we find the proper W for the middle stage. The final result is shown in Fig. 4.8.

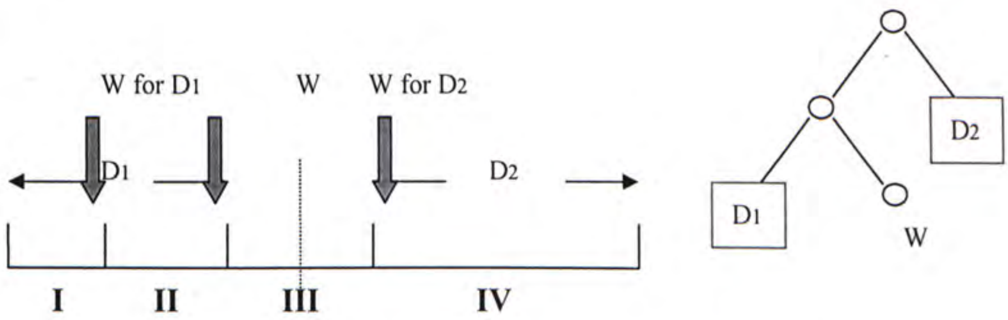

Fig. 4.8 The Recursive Method to find *n* proper CW (6)

However, if $J > J_1$, it means that our beginning assumption that D2 is supposed to have more weights to influence the position of W0 is wrong. We will correct our assumption that D1 has more weights and follow the corresponding algorithm.

At last we can find four kinds of final results based on the analysis above. We show them by the binary decision trees.

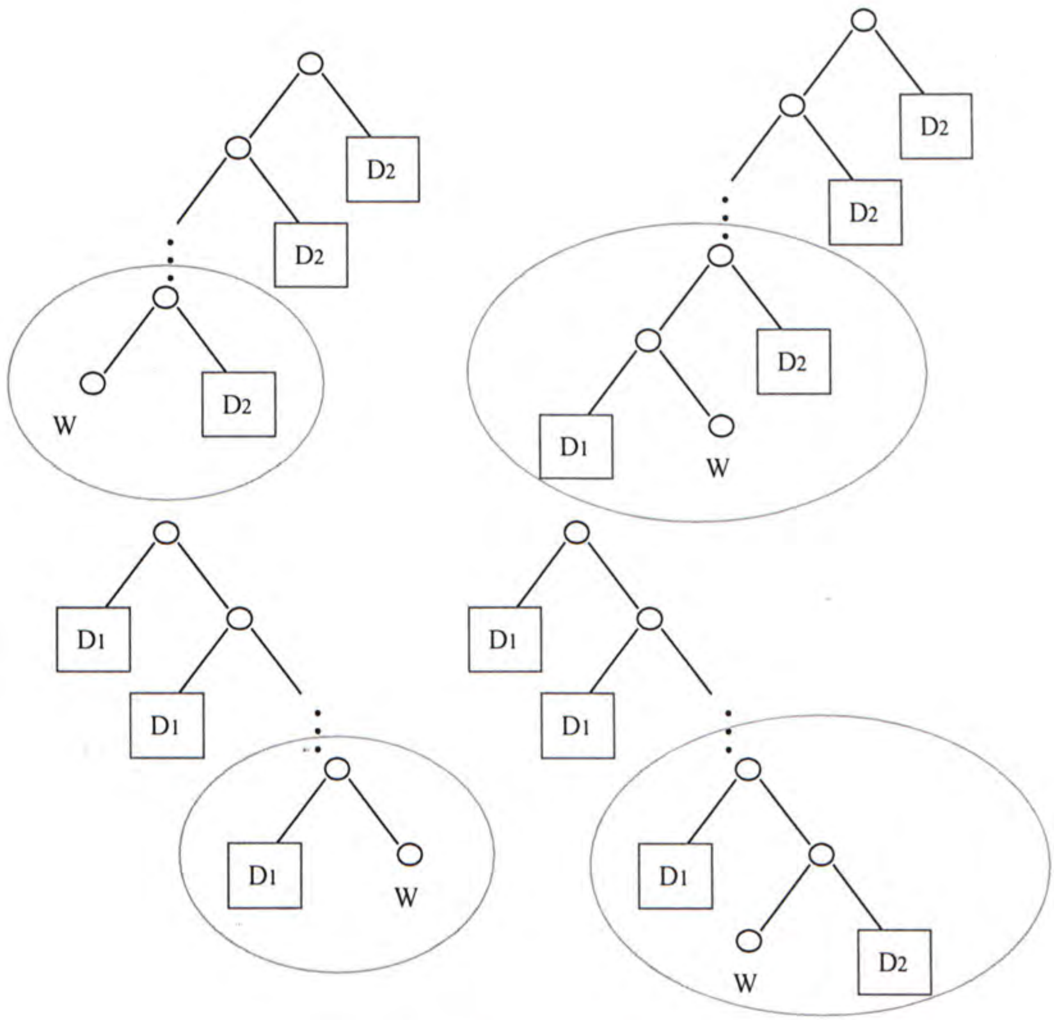

Fig. 4.9 The four kinds of final results

On the four binary trees, the category at the leaf marked by W will use W, categories belonging to D1 use the CW_{max}, and categories belonging to D2 use the CW_{min}.

4.4 Decision Algorithm

We introduced the structure of recursive balance algorithm in Chapter 4.3. In this part, we will patch the decision algorithm in every step. In Fig. 4.3 ~ 4.9, the decision algorithm is shown as the circle in the root of every two subtrees and last optimization for W.

As the analysis in the Chapter III, suppose the number of idle time slots in a transmission cycle be Λ and the number of collisions be Δ. In this algorithm, we would like to choose the proper contention window to minimize the total loss with some constrains.

Suppose that in the former steps it has been determined that the service queues of N_1 categories, which are category 0 to category $N_1 - 1$, will absorb their CW*max* separately; and those of N_2 categories, which are category $L - N_2$ to category $L - 1$, will use their CW*min* separately. Now we suppose that category N_1 to $L - N_2 - 1$ have the same priority. Then at any time slot the probability q that the queue of category j will send its packet is:

$$\begin{cases} 0 \le j \le N_1 - 1 & q_j = \dfrac{1}{E[B_j]+1} & E[B_j] = \dfrac{CW_{\max} j}{2} \\ N_1 \le j \le L - N_2 - 1 & q = q_j = \dfrac{1}{E[B]+1} & E[B] = \dfrac{W}{2} \\ L - N_2 \le j \le L - 1 & q_j = \dfrac{1}{E[B_j]+1} & E[B_j] = \dfrac{CW_{\min} j}{2} \end{cases} \tag{4.5}$$

$E[B_j]$ is the expected back-off time counter value of category j under the current condition; $CW_{\min} j$ and $CW_{\max} j$ means the $CW_{\min}$ and $CW_{\max}$ of category j. W is the CW we need to decide for the category N_1 to $L - N_2 - 1$.

Denote $M = \sum_{j=N_1}^{L-N_2-1} n_j$ means the number of service queues that have not decided their contention window. Consider a tagged queue, called Q, which is in the set of M. The probability p that Q involves in a collision, which is independent of its former transmission history, is

$$p = \text{P}\,[\ge 1 \text{ queues will send too except Q} \mid \text{Q will send its packet at this time slot}]$$

$$= 1 - (1-q)^{M-1} \prod_{j=0}^{N_1-1} (1-q_j)^{n_j} \prod_{j=L-N_2}^{L-1} (1-q_j)^{n_j} \tag{4.6}$$

In Q's transmission cycle, which ends at Q's successful transmission, the distribution of the number of Q's transmissions is geometric with parameter (1-p). Then number of idle time slots Λ is

$$\Lambda = E[B] * \sum_{i=0}^{\infty}(i+1)p^i(1-p) = \frac{E[B]}{1-p} = \frac{W}{2(1-p)} \tag{4.7}$$

And if the duration of a slot time is δ, the loss caused by idle time slots is $\Lambda * \delta$.

In Q's transmission cycle, the probability P that there happens a collision in a time slot is,

$$P = \text{P}\ [\geq 2 \text{ queues will send at the given time slot}]$$

$$= 1-(1-q)^M \prod_{j=0}^{N_1-1}(1-q_j)^{n_j} \prod_{j=L-N_2}^{L-1}(1-q_j)^{n_j} - X \tag{4.8}$$

where $X = \sum_{i=0}^{L-1} n_i q_i (1-q_i)^{n_i-1} \prod_{\substack{j=0 \\ j\neq i}}^{L-1}(1-q_j)^{n_j}$; and when $N_1 \leq j \leq L-N_2-1$, $q_j = q$

Then we can find the number of collisions in Q's transmission cycle is

$$\Delta = (\Lambda + \Delta + \text{Y}) * \text{P}$$

where Y = [average number of successful transmissions in Q's transmission cycle].

Suppose the probability α_j that at any time slot, a successful transmission in one queue called W happens, belonging to category j, is

$$\alpha_j = \text{P [The successful transmission queue is W | transmission queue =1]}$$

$$= \frac{q_j(1-q_j)^{n_j-1}\prod_{\substack{i=0 \\ i\neq j}}^{L-1}(1-q_j)^{n_j}}{P[TransmissionQueue=1]} \quad when \quad N_1 \leq j \leq L-N_2-1 \quad q_j = q \tag{4.9}$$

$$
= \begin{cases}
0 \le j \le N_1 - 1 & \alpha_j = \dfrac{q_j(1-q_j)^{n_j-1}(1-q)^M \prod\limits_{\substack{i=0 \\ i \ne j}}^{N_1-1}(1-q_i)^{n_i} \prod\limits_{i=L-N_2}^{L-1}(1-q_i)^{n_i}}{P[TransmissionQueue = 1]} \\
N_1 \le j \le L - N_2 - 1 & \alpha = \alpha_j = \dfrac{q(1-q)^{M-1} \prod\limits_{i=0}^{N_1-1}(1-q_i)^{n_i} \prod\limits_{i=L-N_2}^{L-1}(1-q_i)^{n_i}}{P[TransmissionQueue = 1]} \\
L - N_2 \le j \le L - 1 & \alpha_j = \dfrac{q_j(1-q_j)^{n_j-1}(1-q)^M \prod\limits_{i=0}^{N_1-1}(1-q_i)^{n_i} \prod\limits_{\substack{i=L-N_2 \\ i \ne j}}^{L-1}(1-q_i)^{n_i}}{P[TransmissionQueue = 1]}
\end{cases} \tag{4.10}
$$

Then Y is

$$
Y = \frac{M\alpha + \sum_{j=0}^{N_1-1}\alpha_j n_j + \sum_{j=L-N_2}^{L-1}\alpha_j n_j}{\alpha} = M + \frac{1}{\alpha}[\sum_{j=0}^{N_1-1}\alpha_j n_j + \sum_{j=L-N_2}^{L-1}\alpha_j n_j] \tag{4.11}
$$

So the Δ can be derived, with Λ in (4.7)

$$
\Delta = \frac{P}{1-P}[\frac{W}{2(1-p)} + M + \frac{1}{\alpha}(\sum_{j=0}^{N_1-1}\alpha_j n_j + \sum_{j=L-N_2}^{L-1}\alpha_j n_j)] \tag{4.12}
$$

With the same assumption in the Chapter III, we use the four-way handshaking mechanism and the penalty of every collision is T = RTS + AIFS. So the loss caused by the transmission is $\Delta * T$.

In a transmission cycle, the total loss is $\Lambda * \delta + \Delta * T$. And there are totally Y successfully transmissions. So finally the total loss Ж per frame caused by idle time slots and transmission collisions is

$$
Ж = (\Lambda * \delta + \Delta * T) / Y
$$

$$
= \frac{\frac{W}{2(1-p)}\delta + \frac{TP}{1-P}[\frac{W}{2(1-p)} + M + \frac{1}{\alpha}(\sum_{j=0}^{N_1-1}\alpha_j n_j + \sum_{j=L-N_2}^{L-1}\alpha_j n_j)]}{M + \frac{1}{\alpha}(\sum_{j=0}^{N_1-1}\alpha_j n_j + \sum_{j=L-N_2}^{L-1}\alpha_j n_j)} \tag{4.13}
$$

where p, P and α_j can be referred in (4.6), (4.8) and (4.10).

Suppose the transmission time of one frame is Tp. Then the bandwidth per frame is Tp +Ж. We cannot shorten the length of Tp but can condense the bandwidth by minimizing the Ж to improve the protocol efficiency.

So given the number of active service queues with different priorities, $\vec{n} = \{n_0, n_1, ..., n_{L-1}\}$, we can get the proper W for category N_1 to $L - N_2 - 1$.

Here we also give three specific cases: S0($N_1 = 0, N_2 = 0$), S1($N_1 = 0, N_2 \neq 0$) and S2($N_1 \neq 0, N_2 = 0$).

For the S0 condition, all the service queues are supposed to have the same priority and no contention window of any category queue has been decided.

In this case, (4.5) becomes:

$$q = \frac{1}{E[B]+1} \qquad E[B] = \frac{W}{2} \tag{4.14}$$

where W is the proper contention window we need now. Then the formula (4.6), (4.8), (4.10) and (4.13) become (4.15), (4.16), (4.17) and (4.18) as below:

$$p = 1 - (1-q)^{N-1} \tag{4.15}$$

$$P = 1 - (1-q)^N - \binom{N}{1} q(1-q)^{N-1} \tag{4.16}$$

$$\alpha = \alpha_j = \frac{q(1-q)^{N-1}}{P[TransmissionQueue = 1]} \tag{4.17}$$

$$Ж = \frac{\frac{W}{2(1-p)}\delta + \frac{TP}{1-P}[\frac{W}{2(1-p)} + N]}{N} \tag{4.18}$$

We can get the optimized W by minimizing formula (4.18) for S0 condition.

For S1 condition, it is determined that the service queues of category $L-N_2$ to category $L-1$ will absorb their CW*min* separately. Under this condition, (4.5) becomes:

$$\begin{cases} 0 \le j \le L-N_2-1 & q = q_j = \dfrac{1}{E[B]+1} & E[B] = \dfrac{W}{2} \\ L-N_2 \le j \le L-1 & q_j = \dfrac{1}{E[B_j]+1} & E[B_j] = \dfrac{CW_{\min} j}{2} \end{cases} \tag{4.19}$$

where W is the proper contention window we need for the category 0 to $L-N_2-1$.

Denote $M_1 = \sum_{i=0}^{L-N_2-1} n_i$, then the formula (4.6), (4.8), (4.10) and (4.13) become (4.20), (4.21), (4.22) and (4.23) as below:

$$p = 1-(1-q)^{M_1-1} \prod_{j=L-N_2}^{L-1} (1-q_j)^{n_j} \tag{4.20}$$

$$P = 1-(1-q)^{M_1} \prod_{j=L-N_2}^{L-1} (1-q_j)^{n_j} - X_1 \tag{4.21}$$

$$X_1 = \sum_{i=0}^{L-1} n_i q_i (1-q_i)^{n_i-1} \prod_{\substack{j=0 \\ j \ne i}}^{L-1} (1-q_j)^{n_j} \quad \text{when} \quad 0 \le i \le L-N_2-1, \; q_i = q$$

$$\begin{cases} 0 \le j \le L-N_2-1 & \alpha = \alpha_j = \dfrac{q(1-q)^{M_1-1} \prod_{i=L-N_1}^{L-1} (1-q_i)^{n_i}}{P[TransmissionQueue=1]} \\ L-N_2 \le j \le L-1 & \alpha_j = \dfrac{q_j(1-q_j)^{n_j}(1-q)^{M_1} \prod_{\substack{i=L-N_1 \\ i \ne j}}^{L-1} (1-q_i)^{n_i}}{P[TransmissionQueue=1]} \end{cases} \tag{4.22}$$

$$\text{Ж} = \frac{\dfrac{W}{2(1-p)}\delta + \dfrac{TP}{1-P}[\dfrac{W}{2(1-p)} + M_1 + \dfrac{1}{\alpha} \sum_{j=L-N_2}^{L-1} \alpha_j n_j]}{M_1 + \dfrac{1}{\alpha} \sum_{j=L-N_2}^{L-1} \alpha_j n_j} \tag{4.23}$$

We can get the proper W by minimizing formula (4.23) for S1 condition.

For S2 condition, it is determined that the service queues of category 0 to category N_1-1 will absorb their CW*max* separately. Under this condition, (4.5) becomes:

$$\begin{cases} 0 \le j \le N_1 - 1 & q_j = \dfrac{1}{E[B_j]+1} & E[B_j] = \dfrac{CW_{\max} j}{2} \\ N_1 \le j \le L-1 & q = q_j = \dfrac{1}{E[B]+1} & E[B] = \dfrac{W}{2} \end{cases} \tag{4.24}$$

where W is the proper contention window we need for the category N_1 to $L-1$. Denote $M_2 = \sum_{i=N_1}^{L-1} n_i$, then the formula (4.6), (4.8), (4.10) and (4.13) become (4.25), (4.26), (4.27) and (4.28) as below:

$$p = 1-(1-q)^{M_2-1}\prod_{j=0}^{N_1-1}(1-q_j)^{n_j} \tag{4.25}$$

$$P = 1-(1-q)^{M_2}\prod_{j=0}^{N_1-1}(1-q_j)^{n_j} - X_2 \tag{4.26}$$

$$X_2 = \sum_{i=0}^{L-1} n_i q_i (1-q_i)^{n_i-1}\prod_{\substack{j=0 \\ j\ne i}}^{L-1}(1-q_j)^{n_j}, \text{ when } N_1 \le i \le L-1,\ q_i = q$$

$$\begin{cases} 0 \le j \le N_1 - 1 & \alpha_j = \dfrac{q_j(1-q_j)^{n_j-1}(1-q)^{M_2}\prod\limits_{\substack{i=0 \\ i\ne j}}^{N_1-1}(1-q_i)^{n_i}}{P[TransmissionQueue=1]} \\ N_1 \le j \le L-1 & \alpha = \alpha_j = \dfrac{q(1-q)^{M_2-1}\prod\limits_{i=0}^{N_1-1}(1-q_i)^{n_i}}{P[TransmissionQueue=1]} \end{cases} \tag{4.27}$$

$$Ж = \frac{\dfrac{W}{2(1-p)}\delta + \dfrac{TP}{1-P}\left[\dfrac{W}{2(1-p)} + (M_2-1) + \dfrac{1}{\alpha}\sum\limits_{j=0}^{N_1-1}\alpha_j n_j\right]}{M_2 + \dfrac{1}{\alpha}\sum\limits_{j=0}^{N_1-1}\alpha_j n_j} \tag{4.28}$$

We can get the proper W by minimizing formula (4.28) for S2 condition.

Based on the analysis in the Chapter 4.3 and 4.4, we get the whole details of the optimization method to find distinct CW values. The Fig. 4.9 is extended as below to show our solution.

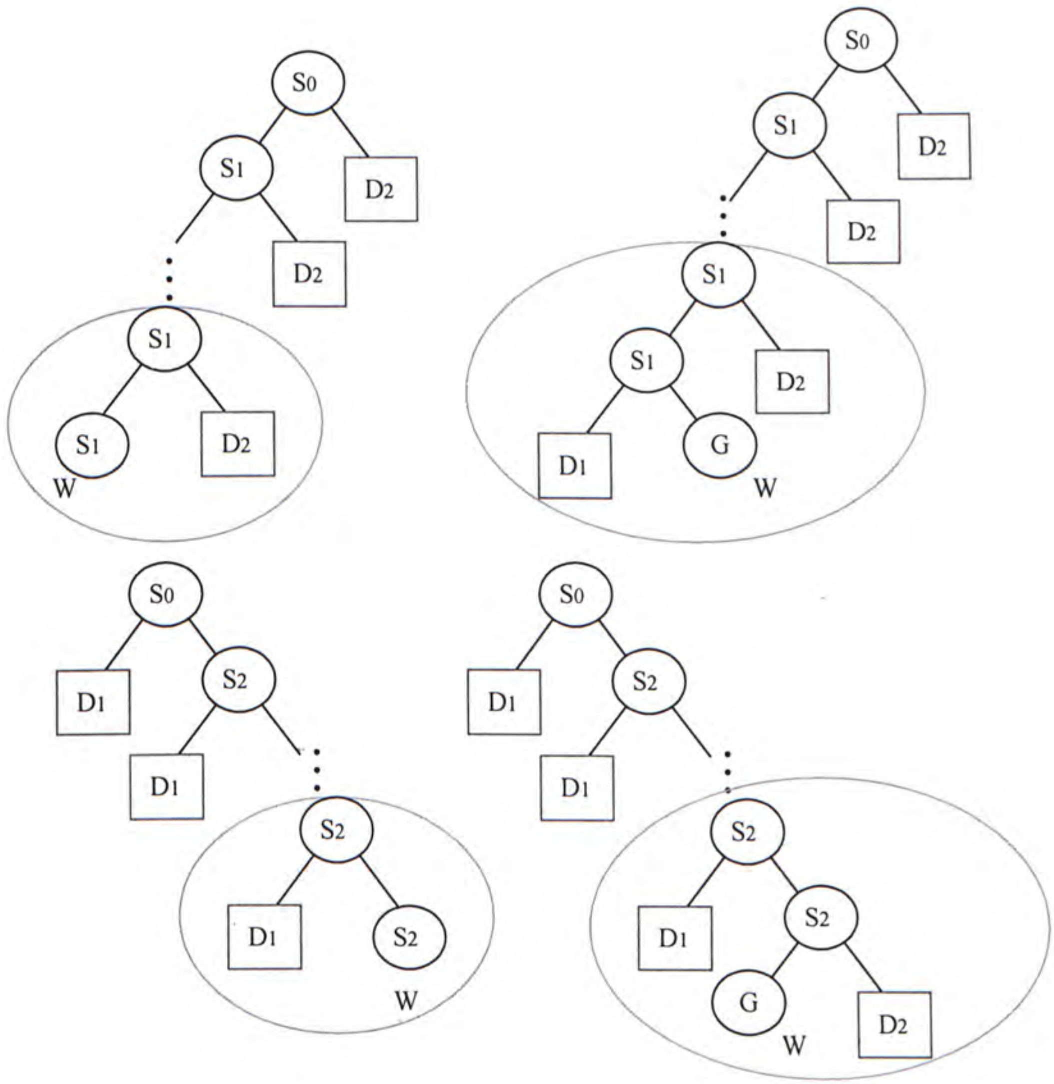

Fig. 4.10 The whole procedure of the optimization method

In the Fig. 4.10, the circles in the boots of subtrees marked with S_0, S_1, S_2 and G mean the optimization methods used for S_0, S_1, S_2 and G conditions. The areas in the green circle show the possible final results.

For the more general conditions, we give the procedure codes as below, where there may be some overlap between the ranges of CW for different categories.

First we use the S_0 condition to get the W_0, and I_0, J_0 from formula (4.2), and D_1, D_2 from formula (4.4).

If $D_1 \le D_2$, we will use the Procedure1 as below:

Procedure1

Input: I_0, J_0, W_0

$D_1 = \sum_{i=0}^{I_0} n_i$, $D_2 = \sum_{j=J_0}^{L-1} n_j$

Use S1 condition ($N_1 = 0, N_2 = D_2$) to get new proper W, and $\begin{cases} W < CW_{\min} J \\ W > CW_{\max} I \end{cases}$ (I, J are newly derived from W)

if ($J < J_0$)

{

if ($J \ne 1$)

{

$I_1 \leftarrow I$; $J_1 \leftarrow J$; $W_1 \leftarrow W$;

Procedure1 (I_1, J_1, W_1)

}

else

{

Category 1 to (L-1) employ their CW*min* separately;

Category 0 employ W;

}

}

else if ($J = J_0$)

{

$I_1 \leftarrow I$; $J_1 \leftarrow J$; $W_1 \leftarrow W$;

$D_1 = \sum_{i=0}^{I_1} n_i$, $D_2 = \sum_{j=J_1}^{L-1} n_j$

Use the G condition ($N_1 = D_1, N_2 = D_2$) to get new proper W, and $\begin{cases} W < CW_{\min} J \\ W > CW_{\max} I \end{cases}$ (I, J are newly derived from W)

```
if (J > J1)
{
    End this Procedure;
    Start Procedure2 (I0, J0, W0)
}
else if (J = J1)
{
    while (I > I1 and J = J1)
    {
        I1 ← I; J1 ← J; W1 ← W;
```

$D_1 = \sum_{i=0}^{I_1} n_i$, $D_2 = \sum_{j=J_1}^{L-1} n_j$

Use the G condition ($N_1 = D_1, N_2 = D_2$) to get new proper W, and $\begin{cases} W < CW_{\min} J \\ W > CW_{\max} I \end{cases}$ (I, J are newly derived from W)

```
    }
    if (J > J1)
    {
        End this Procedure;
        Start Procedure2 (I0, J0, W0)
    }
    if (I = I1)
    {
        Category 0    to I    employ their CWmax separately;
```

Category J to (L-1) employ their CW*min* separately;

Category (I+1) to (J-1) employ W;

}

}

}

However if $D_1 > D_2$, we will use the Procedure2 as below:

Procedure2

Input I_0, J_0, W_0

$D_1 = \sum_{i=0}^{I_0} n_i$, $D_2 = \sum_{j=J_0}^{L-1} n_j$

Use S2 condition ($N_1 = D_1, N_2 = 0$) to get new proper W, and $\begin{cases} W < CW_{\min} J \\ W > CW_{\max} I \end{cases}$ (I, J are newly derived from W)

if ($I > I_0$)

{

if ($I \neq L-2$)

{

$I_2 \leftarrow I$; $J_2 \leftarrow J$; $W_2 \leftarrow W$;

Procedure2(I_1, J_1, W_1)

}

else

{

Category 0 to (L-2) employ their CW*max* separately;

Category (L-1) employ W;

}

}

else if ($I = I_0$)

{

$I_2 \leftarrow I$; $J_2 \leftarrow J$; $W_2 \leftarrow W$;

$D_1 = \sum_{i=0}^{I_2} n_i$, $D_2 = \sum_{j=J_2}^{L-1} n_j$

Use the G condition ($N_1 = D_1, N_2 = D_2$) to get new proper W, and $\begin{cases} W < CW_{\min} J \\ W > CW_{\max} I \end{cases}$ (I, J are newly derived from W)

if ($I < I_2$)

{

End this Procedure;

Start Procedure1(I_0, J_0, W_0)

}

else if ($I = I_2$)

{

while ($J = J_2$ and $I = I_2$)

{

$I_2 \leftarrow I$; $J_2 \leftarrow J$; $W_2 \leftarrow W$;

$D_1 = \sum_{i=0}^{I_2} n_i$, $D_2 = \sum_{j=J_2}^{L-1} n_j$

Use the G condition ($N_1 = D_1, N_2 = D_2$) to get new proper W, and $\begin{cases} W < CW_{\min} J \\ W > CW_{\max} I \end{cases}$ (I, J are newly derived from W)

}

if ($I < I_2$)

{

End this Procedure;

```
            Start Procedure1( I_0, J_0, W_0 )
        }
        if ( I = I_2 )
        {
            Category 0       to I        employ their CWmax separately;
            Category J       to (L-1)    employ their CWmin separately;
            Category (I+1) to (J-1)   employ W;
        }
    }
}
```

4.5 Model Validation and Simulation Results

We still present the detailed simulation studies for extended proposed protocol compared with the IEEE 802.11standards with *Matlab* 6.5 and *ns-2* simulator. All values of the parameters in the simulation are shown in the Table 3-1 except some adjustments in Table 4-1.

Table 4-1 The Additional Simulation Parameter Values

Parameters	Values
Voice frame payload size (category 0)	1000 bytes
Video frame payload size (category 1)	1000 bytes
FTP frame payload size (category 2)	1000 bytes
Average arrival rate for Voice	0.000001 pf/sec
Average arrival rate for Video	0.000001 pf/sec
Average arrival rate for FTP	0.00001 pf/sec

Now we give the relatively small average arrival rates for all these three categories and big number of mobile stations in the Wireless LAN. In this case, the simulation result curve will be smoother.

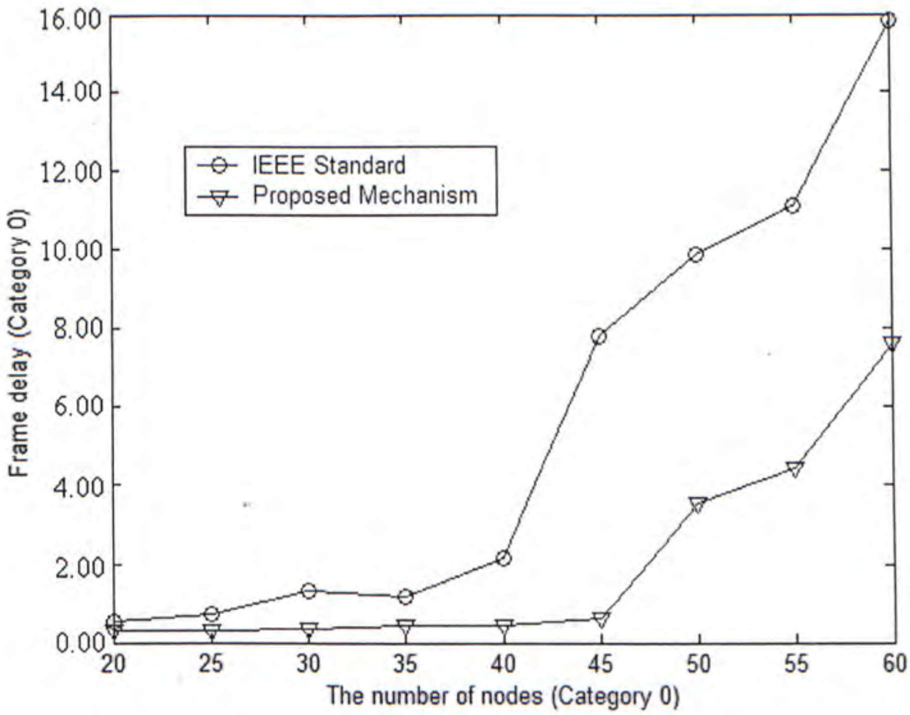

Fig. 4.11 The Frame Delay VS. The Number of nodes (Category 0)

The frame delay curve of category 0 is shown in Fig. 4.11. We can see clearly that the delay of this time sensitive service is reduced much. The average delay of proposed protocol is less than 40% of that of IEEE standards through these points we get in the curve in Fig. 4.11. In addition, we know that the system performance will decrease quickly when the number of mobile stations exceeds some certain value. In Fig. 4.11, the frame delay of IEEE standard increases greatly when the number of nodes reaches 45. However when the number of nodes reaches 50, the frame delay of proposed protocol begins to increase much.

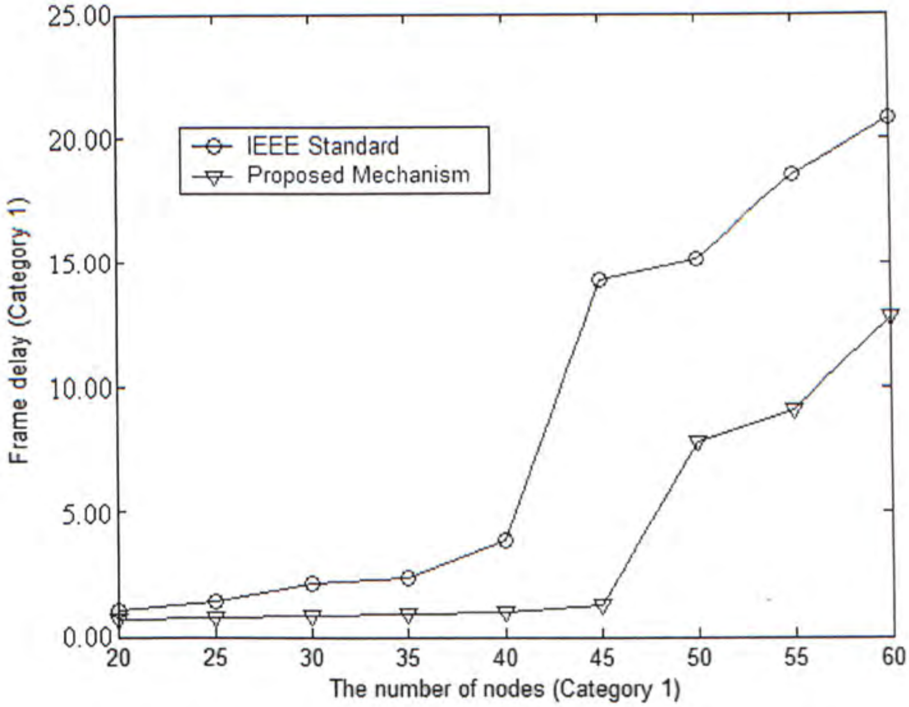

Fig. 4.12 The-Frame Delay VS. The Number of nodes (Category 1)

The frame delay curve of category 1 is shown in Fig. 4.12. We can also get the similar result As shown in the fig. 4.11. Now the average delay of proposed protocol is less than 50% as that of IEEE standards.

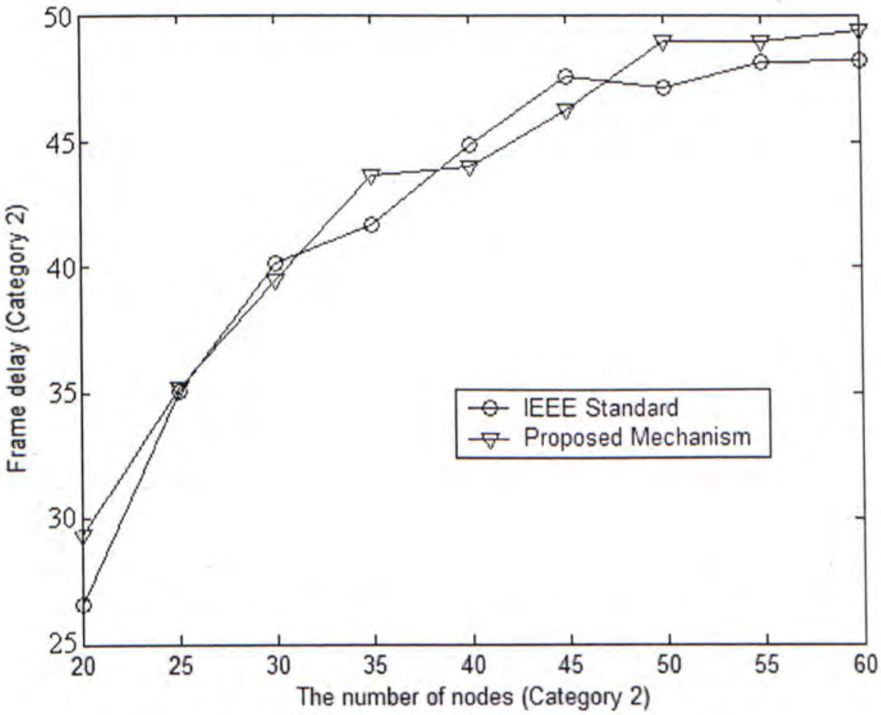

Fig. 4.13 The Frame Delay VS. The Number of nodes (Category 2)

The frame delay curve of category 2 is shown in Fig. 4.13. Although category 2 is not time sensitive service, the frame delay got from proposed protocol and IEEE standard maintain the same level. In other words, we cut down the delays of category 0 and 1 significantly, and keep the delay of category 2 not influenced much at the same time.

CHAPTER V

Further Discussion about the CW design

Abstract

In the analysis of the former chapter, we follow the recursive balance method to get the proper CW for different categories. The only parameters that will influence the choices in the binary decision tree are the number of active queues and CW_{min} and CW_{max} of different traffic classes, which have been determined before hand. The number of active queues cannot be changed artificially. But we can change the CW_{min} and CW_{max} to guarantee that our choice in the binary decision tree is proper.

- Influence of the ranges of CW

  In this part, we will show the obvious influence of the CW ranges. The unfitted ranges will demolish the system performance badly. Continuing the discussion before, we will explain the reason and give the bound line for the suitable CW range.

- Proposal for adjusting CW

  We lay out the problems in Chapter 5.1. In this part, we provide some proposed solutions. Through some of them are not matured and accurate, they do give the directions in the future.

5.1 Influence of the ranges of CW

In the recursive balance algorithm introduced in the previous chapter, we find the distinct CWs for different classes according to the number of active queues. However there is still a system parameter that affects our decisions much. It is the ranges of CW.

In the current IEEE 802.11 protocols, the ranges of CW are determined in advance as the system parameters and cannot be changed in the application no matter what situation happens. It is apparently not adaptive in the high speed transmission rates and QoS requirements. These parameters will influence the system performance greatly ([27]~[33]). The ranges of CW in the current protocol is shown in the Table 5.1

Table 5-1 The Default ranges of CWs in the IEEE protocol

AC	CW_{min}	CW_{max}	Designation
0	3	7	Voice
1	7	15	Video
2	15	1023	Video Probe
3	15	1023	Best Effort

In the Table 5.1, we can see that the ranges of categories for voice and video are quite small. The fundamental idea is to reduce the idle time slots to increase the transmission probability. The service of voice and video are time-sensitive, so we must guarantee that the delay should be as small as possible. And the ranges above cannot be changed to tell the different priority.

However the well-meaning idea conflicts with the practical conditions.

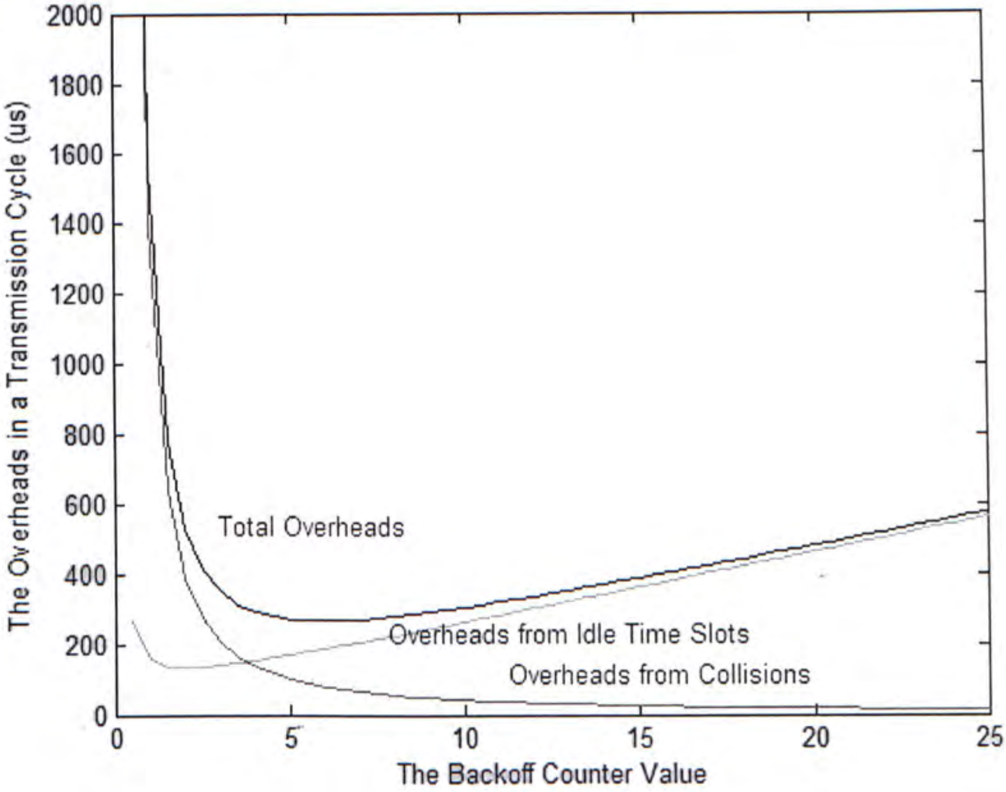

Fig. 5.1 The Analysis of the Ranges of CW

In the Fig. 5.1, the X axis is the back off counter value and Y label is the system overheads in one transmission cycle (Refer to formula (10) and [34]). The curve showing the overheads caused by the collisions is roughly an exponential curve. The curve showing the overheads caused by the idle time slots is roughly a linear curve when the back off counter value is bigger than some value.

In the beginning, when the back counter value is small, the collision probability is very high and the penalty of collisions is correspondingly great. Now the total overhead is mainly dominated by the collisions.

When the back off counter value we absorb is increasing, the collision probability is smaller and smaller. Now the overhead is mainly caused by idle time slots and forms a linear curve verse back-off counter value.

We can see clearly in Fig. 5.1 that when the back off counter is smaller than a certain value, there is too much overhead. It is roughly exponential verse the back off counter. If we use the pre-determined parameters in the Table 5.1, the system performance will totally collapse even there are just a few queues belonging to the first or second categories.

In the Fig. 5.1, we use four active queues. If they are the four customers in one Wireless LAN wanting to call others through the network, they will use the CW from 3 to 7. That means their back off counter value is 1.5 to 3.5. From the Fig. 5.1 we can see that the whole efficiency decreases very quickly and all queues cannot transmit their frames on time. But the condition that four customers in the Wireless LAN want to use the voice or video is very common.

Originally we give the smaller CW range to the category with higher priority in order to reduce its delay. However now the smaller CW range become the major reason to increase its delay and influence their transmission badly. It is not acceptable in the future network with many time sensitive services.

5.2 Proposal for adjusting CW

When we find the problems in the design of the CW ranges, we want to give some proposed solutions. They have not been very matured and accurate. But they can give our future directions and become our future work.

First we should dynamically adjust the CW instead of determining them before hand. As we know, there are only a few materials to discuss the effectual way to design the range of CW for different categories. However we can find the proper way through our analysis in the former chapters. In the view of overheads, we can design the ranges of CW according to the number of active nodes. As long as we give distinct CW ranges to different categories, the priority can be provided. If there are too many customers in the Wireless LAN, the bandwidth is not enough no matter how we design the MAC protocol. We can employ PCF (Point Coordination Function) or give different users separate CW to guarantee that some of them will be transmitted to increase the loading quickly.

Second we can change the method to choose the back off counter value in the (0, W-1). We cannot control this value easily in this way. Instead we can choose it in (S, W-1) where S is the threshold. In this case, we can constrain the value in the range we expect. It will abstain that the counter value is too small.

CHAPTER VI

Conclusion

In this thesis we studied the DCF (Distributed Coordination Function), which is the major algorithm in the MAC protocol of Wireless LAN. It introduces many important concepts, such as IFS (Inter Frame Space), time slots, but the basic design idea meets some inaccuracies. First it uses number of collisions to hypothesize the number of active nodes in the Wireless LAN for the simple implementation. But these two factors do not have the direct relationship all the time. Second it uses the binary increasing-only mechanism, which cannot be suitable for all the conditions. Because of these two reasons, it is too difficult to derive the proper CW, whose value does influence the whole system performance.

Based on these problems above, we introduce a novel MAC protocol, which is designed for the infrastructure network. In the infrastructure network that is employed most presently, AP is the core and all the stations should work under the control of AP. We can impose this characteristic to improve the MAC protocol. In our proposed protocol, we design the mechanism to collect the number of active nodes, the optimization method to get the optimized CW value to minimize the total overheads caused by idle waiting time and penalty of collisions, and the rules for the stations to adjust their counter values according to the new CW value. All these rectification can be realized just through software updating and then practical in the network. The additional overheads imported by the new protocol are very limited but the optimization method and simulation results both show that our protocol reduces the overheads significantly and the system efficiency improves greatly.

In the future Wireless LAN, higher transmission rates and service differentiation are required. All the packets from the high layers should be sorted in conformity to their time sensitive criteria. Then there are more than one queue in a station and all these queues will work independently. So each of them needs a CW to choose its counter value. We extend our protocol by remodelling the frame structure and introduce the recursive balance algorithm to find many CW. There are normally less than 6 categories in the protocol; otherwise the multiple queue incorporation is too intricate and unnecessary. So the computation complexity of recursive balance method is restricted. Although the analysis of decision algorithm is a little complicated, the whole procedure can be finished quickly in hardware by the final results we get. We also validate our advance model through the simulation. It shows that the protocol can adequately limit the delay of time sensitive service and enhance the system throughput by reducing the overheads and balancing the different categories.

Besides these novel protocols we introduced above, we introduce some valuable concepts in our analysis. First we invent the concept of "virtual time slot" compared with the normal time slot. It is a short cut to analyze the Wireless LAN system or understand others' work in this area. Second we introduce the "transmission cycle", which is the service time of one frame. And we divide it into two parts: overhead and payload, which gives us a direct way to improve the protocol efficiency.

In the end, we give some further discussion about adjusting CW ranges, which is also an important issue in the Wireless LAN through our analysis and simulation. It is sarcastic that the smaller range proposed to shorten the delay becomes the major reason to augment delay and lessen the throughput. However there have been little materials to find a proper way to study this problem. It is possible to find the relationship between the range of CW and system performance with our analysis. Then we can find the proper CW range to adapt diverse situations. We also provide the proposals to some specific problems. They are not sophisticated but howbeit give us the future directions.

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